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NUCLEAR DIVISION

7850:0415

NERVA RELIABILITY PROGRAM SUMMARY

JANUARY 1970

TECHNICAL DISCUSSION

Prepared for AEC - NASA Space Nuclear Propulsion Office

NERVA Program Contract SNP-1

AEROJET
GENERAL TIRE
GENERAL

AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

MASTER

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AEROJET GENERAL

7850:0415

NERVA RELIABILITY PROGRAM SUMMARY

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TECHNICAL DISCUSSION

Prepared for AEC - NASA Space Nuclear Propulsion Office

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NUCLEAR ROCKET OPERATIONS

CLASSIFICATION CATEGORY

UNCLASSIFIED

CLASSIFYING OFFICER

Jan 31, 1970

DATE

AEROJET-GENERAL CORPORATION

A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

STATUS REPORT PREPARED FOR

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

January 1970

NERVA PROGRAM

CONTRACT SNP-1

NUCLEAR DIVISION
AEROJET-GENERAL CORPORATION
A SUBSIDIARY OF GENERAL TIRE AND RUBBER CORP.

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STATUS REPORT PREPARED FOR

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

1.0 INTRODUCTION

1.0 INTRODUCTION

This is an informal compilation of analyses, memoranda, procedures and reports published by the NRO Reliability Section between 15 July 1969 and 31 December 1969. The purpose of this report is to appraise cognizant program management personnel, at SNPO-C, WANL, and NRO, of progress toward established program objectives.

STATUS REPORT PREPARED FOR

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

2.0 RELIABILITY MANAGEMENT, POLICIES AND PROCEDURES

MEMORANDUM

TO: P. P. Ventura

DATE: 21 August 1969
7850:M0258

FROM: W. M. Bryan

SUBJECT: Reliability Data Items

COPIES TO: J. J. Beereboom, H. F. Gallagher, B. Mandell, J. H. Ramsthaler, S. A. Varga
NTO: W. H. Bushnell

In a meeting with L. Nichols, SNPO-C on 13-14 August 1969, tentative agreement was reached on the number of AFSCM/AFLCM 310-1 reliability data items to be utilized on the NERVA Program. This list is shown below along with the current status and pertinent remarks. Recommended Form 9's for new data items will be prepared and submitted during CY 70.

Data Item	Form 9 Status	Remarks
R-101	In use	Minor modifications currently being negotiated
R-102	-	Not applicable - maintainability item.
R-103	See R-202	Not applicable - maintainability item.
R-104	-	Not to be used.
R-105	-	Subject to be covered in Reliability Procedure NRP 400. Data Item will not be used.
R-106	Being negotiated	Reliability Test and Evaluation Plan.
R-107	-	Not applicable - maintainability item.
R-108	-	Subject to be covered in Reliability Procedure NRP 400. Data Item will not be used.
R-109	To be prepared	Annual report to be required. Will not be related to program milestones.
R-110	-	Not to be used. Reliability status to be provided in program quarterly report.
R-111	-	Not applicable - maintainability item.
R-112	To be prepared	Reliability Test and Evaluation Reports.

2.1

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Data Item	Form 9 Status	Remarks
R-113	-	Not applicable - maintainability item.
R-114	-	Subject to be covered in future reliability procedure. Data Item will not be used.
R-115	-	Not to be used.
R-116	-	Not to be used.
R-202	In use	Reliability data report to be issued at DRB, PDR, CDR, etc.

W. M. Bryan

W. M. Bryan, Supervisor
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Bryan 8/20/69
CLASSIFYING OFFICER DATE

MEMORANDUM

TO: W. M. Bryan

DATE: 28 August 1969
7850:M0263

FROM: L. P. Burke

SUBJECT: Radiation Effects Data in Instrumentation and Controls Reliability

COPIES TO: J. W. Brewer, J. W. Conant, J. H. Ramsthaler, E. A. Sheridan, J. E. Stadig
NTO: W. H. Bushnell

REFERENCE: (a) Meeting 25 August 1969, L. P. Burke and J. E. Stadig, same subject

Reference (a) meeting was held to assist in work that has begun on collecting radiation effects data. These data will be interpreted into "K" factors for use in the Instrumentation and Controls reliability equations.

Information obtained from Reference (a) has shown the possibility of using existing computer programs, such as PAN E, "Performance Analysis of Electronic Circuitry", as a subroutine in the I & C system reliability computer program. J. Stadig was requested to provide access to this and other programs at his convenience.

J. Stadig is also preparing a program plan for continued radiation effects work, and requested Department 7850's assistance in orienting his plan toward acquisition and preparation of data significant for use in the reliability analysis of the Instrumentation and Controls subsystem.

A meeting to review Department 7850's effort on this matter is tentatively scheduled for early next week.

L. P. Burke
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Bryan 8/28/69
CLASSIFYING OFFICER DATE

2.3

MEMORANDUM

TO:	P. P. Ventura	DATE:	22 September 1969 7850:M0278
FROM:	R. E. Lavond		
SUBJECT:	Reliability/Trend Data Review of Data Item C-100 Data and Documentation Management Plan (Supplemental Plan)		
COPIES TO:	J. J. Beereboom, W. M. Bryan, J. L. Goldin, J. M. Klacking, B. Mandell, J. H. Ramsthaler NTO: W. H. Bushnell		
REFERENCE:	(a) Memo 7810:1225M, dated 9 September 1969, P. P. Ventura to Distribution, same subject		

Per your request, subject data item has been reviewed for acceptability to Reliability. The following comments are forwarded for consideration:

a. No changes are considered necessary to the text.

b. Figures 2-3, 2-12, 2-14 and 2-17 should be revised as follows:

(1) "Criteria and/or requirements" should be li· ·d for "Trend Data, Malfunction/Failure reports, and Parts Qualification", a. a DRB requirement.

(2) A requirement to "verify all specification requirements" in CEI and ECC specifications should be added for PDR.

(3) Trend Data Characteristics should be required for PDR under data item entitled "Document Manufacturing Program".

For further information please contact the undersigned at extension 5-6975.

R. E. Lavond

R. E. Lavond
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Bryan 9/23/69
CLASSIFYING OFFICER DATE

2.4

M E M O R A N D U M

TO: D. Holzman DATE: 3 November 1969
7850:M0317

FROM: J. R. [illegible]nthaler

SUBJECT: Review of ETS-1 Maintainability Program Operations Plan

DISTRIBUTION: J. J. Beerehoom, W. M. Bryan, E. Clarbergen, J. S. Goddard, E. L. Hauslar, B. Mandell, W. D. Wayne

NTO: W. H. Bushnell

REFERENCE: (a) Memorandum 7050:M4071, D. Holzman to Distribution, dated 20 October 1969, Subject: Request for Review of ETS-1 Maintainability Program

(b) Memo NTO-M-78777, W. H. Bushnell/A. P. Weber to W. E. Mazor, Subject: NTO Reliability/Maintainability Program CY'70, dated 24 October 1969

A review has been completed of the proposed ETS-1 Maintainability Program as defined in Reference (a). The plan as presented is a good maintenance program for valves and mechanical parts, but does not represent an overall maintainability effort for the facility.

ETS-1 currently appears as a major constraint in the NERVA testing program and time delays for equipment malfunctions will have major programmatic implications. It is strongly recommended the plan be expanded to include all elements of a maintainability program.

A total maintainability program would include elements as outlined below.

1) Identify current configuration of all equipment.

2) Accumulate failure rate history.

3) Determine costs of test delays to the program.

4) Study means of reducing test delays due to equipment malfunctions.

   (a) Replace equipment
   (b) Modify equipment
   (c) Preventative maintenance
   (d) Accept known risks of test delays

5) Modify equipment per cost studies and implement computerized maintenance program.

2.5

The proposed program addresses itself principally to items 1, 4c and parts of 5. The [illegible] studies are primarily those which justify and form the basis for the subsequent maintenance activities. Without these studies NRO will always be subjected to second guessing and criticism by the customer when tests are delayed by facility malfunctions.

If it is decided not to conduct a complete maintainability program, the following are recommended minimum additions to the proposed maintenance program:

1) The plan should include electronics, an area that has given many problems in past testing.

2) The program should be integrated with the facility reliability effort (Reference (b)) since definition of historical problems is an important part of any maintenance plan.

J. B. Ramsthaler, Manager
Reliability & Safety Analysis Section
Nuclear Rocket Operations

APPROVED:

H. J. Beereboom, Manager
Systems Department
Nuclear Rocket Operations

2.6

MEMORANDUM

TO: E. A. Sheridan

DATE: 7 November 1969
7850:M0330

FROM: W. M. Bryan

SUBJECT: Reliability Training

COPIES TO: L. P. Burke, V. M. H. Chang, H. F. Gallagher, W. P. Gilles, A. J. Mihanovich, H. Musgrove, J. H. Ramsthaler, M. D. Smith, E. J. West

ENCLOSURE: (1) Lecture Series

Enclosure (1) presents a revision to the lecture series by Department 7850 to provide training to Department 7820 personnel in the use of Reliability analytical techniques. Additional lectures will be added as requirements are identified.

W. M. Bryan

W. M. Bryan, Supervisor
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE

2.7

Enclosure (1)
7850:M0330

LECTURE SERIES

Date	Title	Speaker
Completed	Reliability Analysis of the 10-Channel Averager - Part I	J. W. Brewer
Completed	Introduction to Reliability	J. H. Ramsthaler
17 Nov. 1969	Reliability Analysis of the 10-Channel Averager - Part II	J. W. Brewer
20 Nov. 1969	Introduction to Statistics I	M. W. Layard
25 Nov. 1969	Introduction to Statistics II	M. W. Layard
2 Dec. 1969	Applied Statistics	A. J. Mihanovich
8 Dec. 1969	Circuit Reliability Analysis I	J. H. Morison
15 Dec. 1969	Monte Carlo Simulation Techniques I	P. H. Raabe

2.8

M E M O R A N D U M

TO: W. E. Stephens DATE: 16 December 1969
7850:M0372

FROM: J. H. Ramsthaler

SUBJECT: Reliability and Safety Requirements for Trade Studies

DISTRIBUTION: L. Cota, G. H. Brock, W. E. Durkee, F. Farquhar, W. J. Houghton, G. D. Hart, L. D. Johnson, C. F. Leyse, P. Kluger, B. Mandell, W. W. Madsen, R. R. Stiger, D. F. Vanica, E. A. Warman, J. L. Watkins, N. F. Wessinger, Section 7850 Personnel

REFERENCE: (a) Memo J. H. Ramsthaler to B. Mandell, 7850:M0370 dated 16 December 1969, Subject: Report on Reliability Meeting with R. W. Schroeder, SNPO-C, on Dec. 11/69

Reliability and safety are required disciplines to be considered as trade-off factors in all trade studies, the same as are, for example, performance and weight. Accordingly, all trade study reports should include sections on reliability and safety. It is anticipated that for a minor number of trade studies, reliability and/or safety will not be factors for consideration. In these cases, reliability and/or safety sections which present the logic and justification why these disciplines were not included as trade-off factors should still be provided. In no case should the omission of a reliability and/or safety input from a trade study report result in the impression that these disciplines were mistakingly overlooked. Dr. L. Nichols has informally indicated that any trade study report which does not include a failure mode analysis will not be satisfactory to SNPO. At a meeting with R. W. Schroeder on reliability, Reference (a), he was very critical of the WANL reliability effort and from his comments, it is my conclusion their principal error was the lack of a failure mode analysis.

Reliability and Safety Analysis personnel (Section 7850) are available and should be used to provide the reliability and safety analyses required to support the trade studies. Trade Study project engineers should make requests for reliability and safety analysis to the undersigned, or specific requests should be made for reliability analysis to W. M. Bryan or for safety analysis to D. S. Duncan. Because of the large number of trade studies in progress, the maximum lead time possible should be provided to Section 7850 to conduct the required analysis.

2.9

Early coordination with Section 7850 for reliability and safety analysis during the conduct of the trade studies will facilitate the review by Secton 7850 of the final S-54 reports.

J. H. Ramsthaler, Manager
Reliabiltiy & Safety Analysis Section
Nuclear Rocket Operations

APPROVED:

for B. Mandell, Manager
Engine System Department
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
12/16/69

2.10

STATUS REPORT PREPARED FOR

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

3.0 RELIABILITY ANALYSIS

MEMORANDUM

TO: W. J. Houghton

DATE: 3 September 1969
7850:M 0245

FROM: R. E Lavond

SUBJECT: Trade Study 002 - Post Shutdown Space Operations

COPIES TO: J. H. Altseimer, E. K. Bair, D. Buden, S. E. Colucci, J. M. Klacking, P. Kluger, B. Misra, G. G. Strucel, E. V. Krivanec
NTO: W. H. Bushnell

ENCLOSURES:
(1) Tabulation: Null Concept Reliabilities
(2) Schematics of Pressure Fed System
(3) Schematics of "Pump" Fed Systems
(4) Null System - Reliability Diagrams
(5) Reliability Math Models - General (for "n" cycles)
(6) Failure Rates NERVA Controls Components
(7) Reliability Calculation Matrices
(8) Concept Events

Summary

This analysis addresses itself to estimating the reliability effect of various thrust nulling concepts on NERVA engine functions. The eight cooldown-thrust nulling concepts analyzed are shown in Enclosures (2) and (3). As shown in Enclosure (1) the range of failure rates (e.g., the compliment of Reliability is the Failure Rate) is estimated to be from 4416 failures per million (for sigma concept) to 6707 for 5b concept. Sigma is therefore about 34% better than 5b, about 29% better than the average pressure fed system, about 18% better than the average of all systems, about 4% better than the average tank pressure fed system and also about 4% better than the next best system (concept delta).

Due to decreased complexity, tank fed systems are about 16% better than pump fed systems.

Variations within the tank fed concepts are primarily due to:

a. Reduced leakage paths during thrusting because of redundancy caused by CNDVs or TNDVs, and

b. Ease of cooling down due to a minimum of valving changes required, and because of stand-by redundancy in cases using PSOVs for pulse cooling flow.

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As indicated in Enclosures (5) and (7), all components are assumed to be cycle sensitive. Each component or component group is "cycled" as often as required by the mission to account for reliability degradation during the mission. The results, Enclosure (1), are the current failure rate ~~reliability~~ estimates for the cooldown thrust nulling systems.

Satisfaction of PERT Items

This transmittal completes PERT events 301 through 310 and 312.

Conclusions and Recommendations

1. Tank pressure fed thrust nulling concepts are more reliable than pumped concepts.

2. To be acceptable, axial thrust nulling valves must be of the analog variety.

3. There is no significant reliability difference between ullage gas and liquid cooling concepts.

4. There is no significant reliability difference between radial and axial nulling concepts.

5. Based only on reliability considerations, the tank fed, radial nulled, liquid hydrogen cooled sigma concept is judged superior to the other concepts (provided analog TNVs are incorporated).

Discussion

To standardize the analysis, each concept was (mathematically) considered to undergo the rigors of Mission A with its two rendezvous with a synchronous space station and return. To facilitate calculations, each concept was analyzed ~~for~~ its ~~impact on~~ ability to produce thrust, to cooldown, to null and to coast.

These results are presented in Enclosure (1) for each of the eight concepts. Enclosures (2) and (3) contain schematic diagrams of tank pressure-fed and pumped concepts respectively.

The logic employed for each concept is indicated in Enclosure (4) - "Null Systems -- Reliability Diagrams". While Enclosure (5) presents the general reliability mathematical models used to calculate the probabilities of series, parallel and stand-by cases for "n" cycles.

Failure rates developed for R-202 were used for this analysis and are summarized in Enclosure (6). Components having similar functional requirements being assigned similar failure rates to assure consistent results. Enclosure (7) illustrates the results of substituting probabilities of success (i.e., 1.0 - Failure Rate) into the math models of Enclosure (5) as indicated by the logic of Enclosure (4). These results indicate the probability of proper operation for the applicable number of cycles. The products of these probabilities is the probability of success for that concept and is the final reliability figure presented. Concept functional requirements are listed in Enclosure (8) for each mission phase.

R. E. Lavond

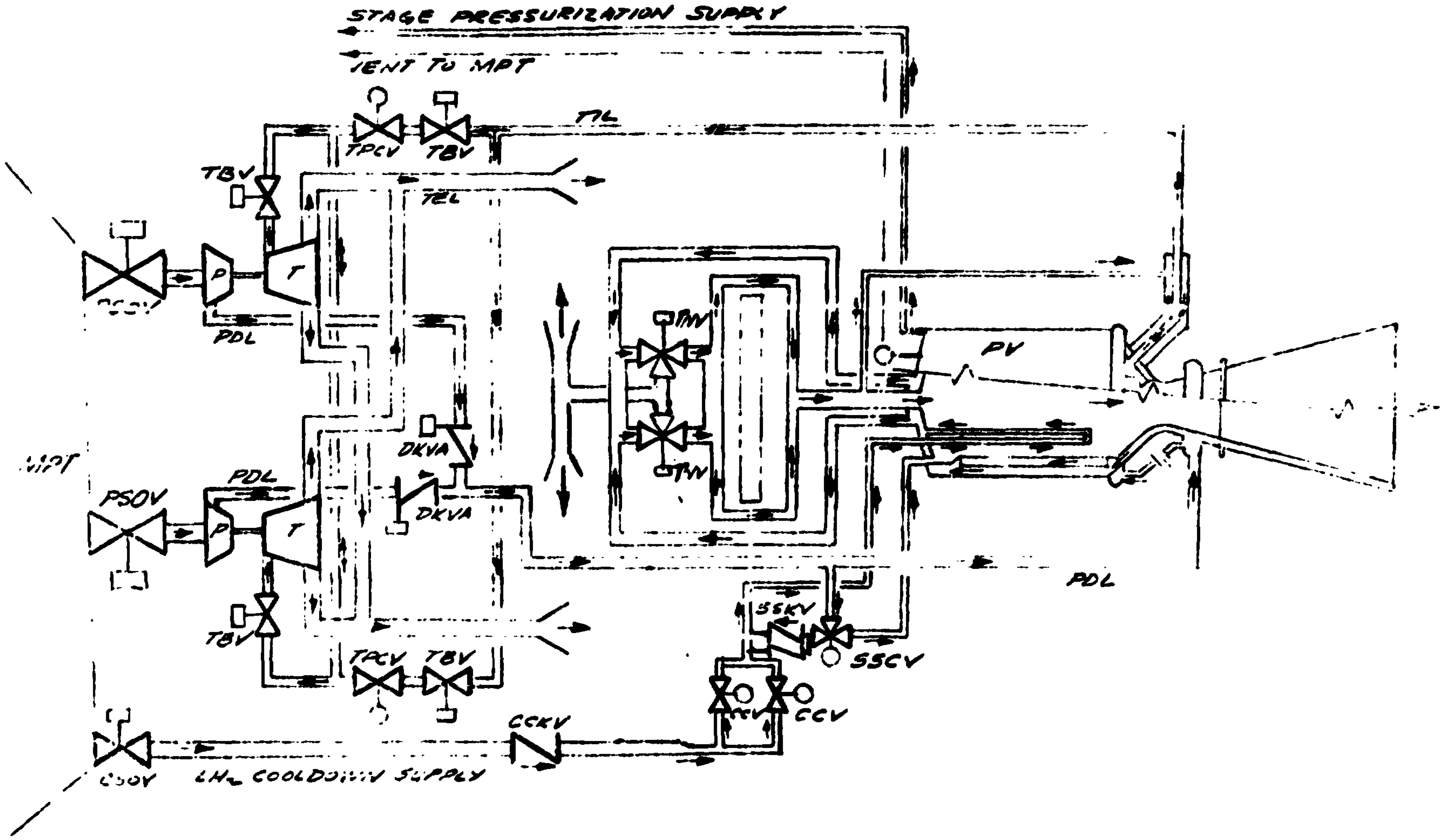
THRUST [illegible] CONCEPT
FAILURE RATES (IN DPM'S)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	400	<0.1	400	<0.1	<0.1	<0.1	<0.1	<0.1	8
[illegible]	2705	3670	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] 150
[illegible]	1151	1351	1151	1351	1151	1151	1351	1351	4 or [illegible]
COAST	400	400	401	401	401	401	401	401	[illegible]
MISSION A	4419	4416	4799	4601	6677	6707	5750	5761	

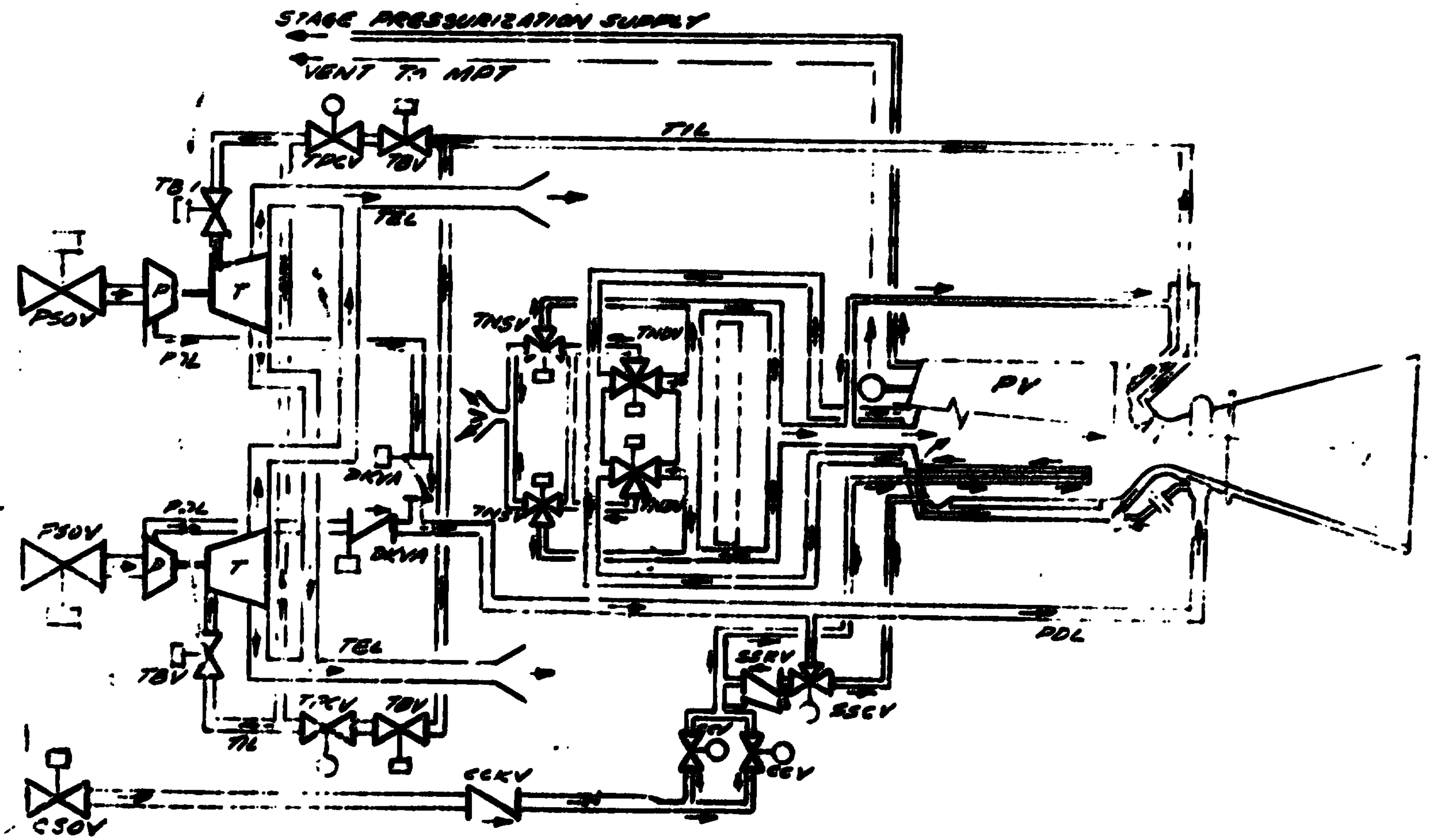
-1.0

3.4

TANK PRESSURE LH_2 COOLDOWN (RADIAL TN)
("SYSTEM "OMEGA")



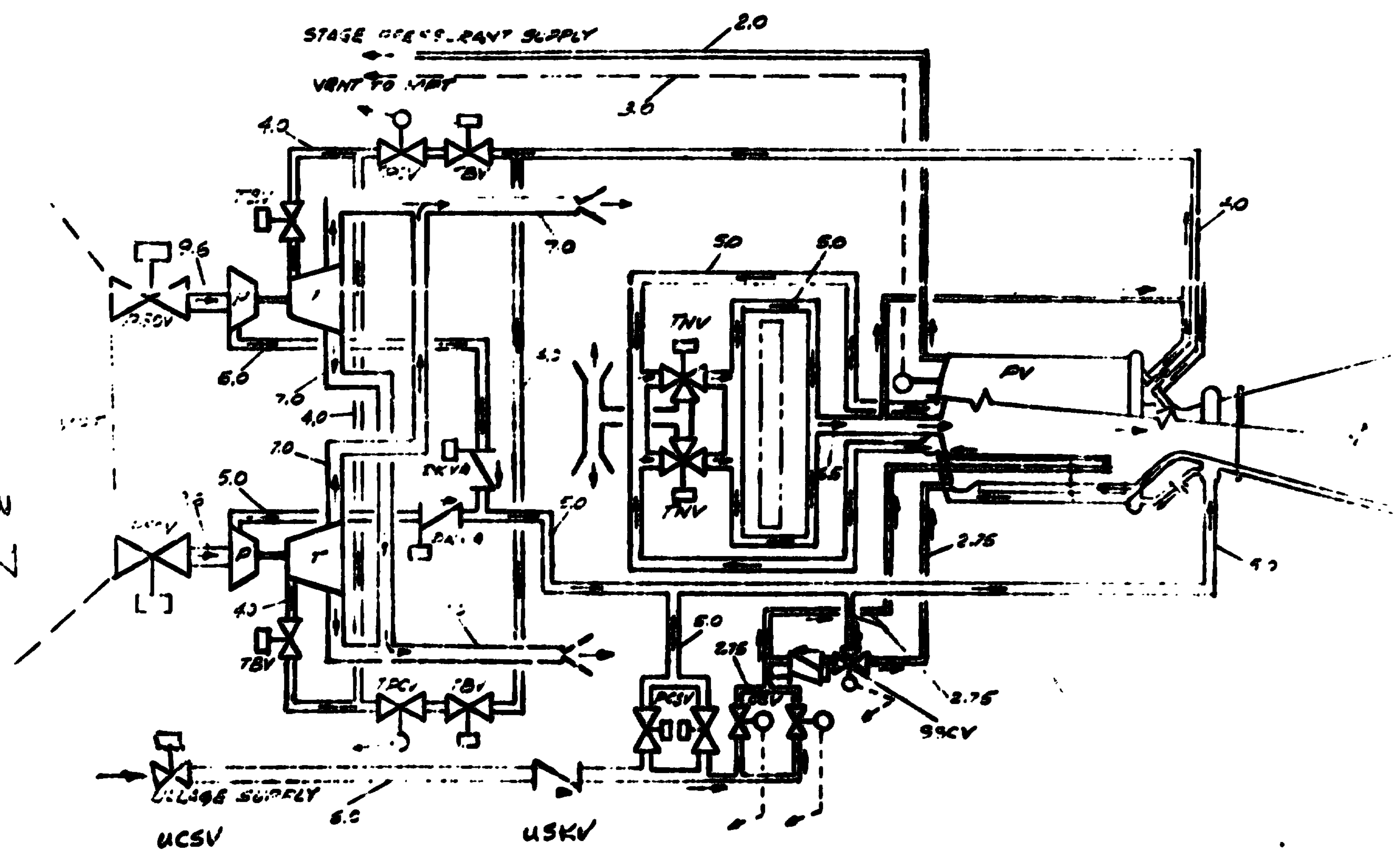
TANK PRESSURE LH_2 COOLDOWN (AXIAL TN)
(SYSTEM "SIGMA")



3-6

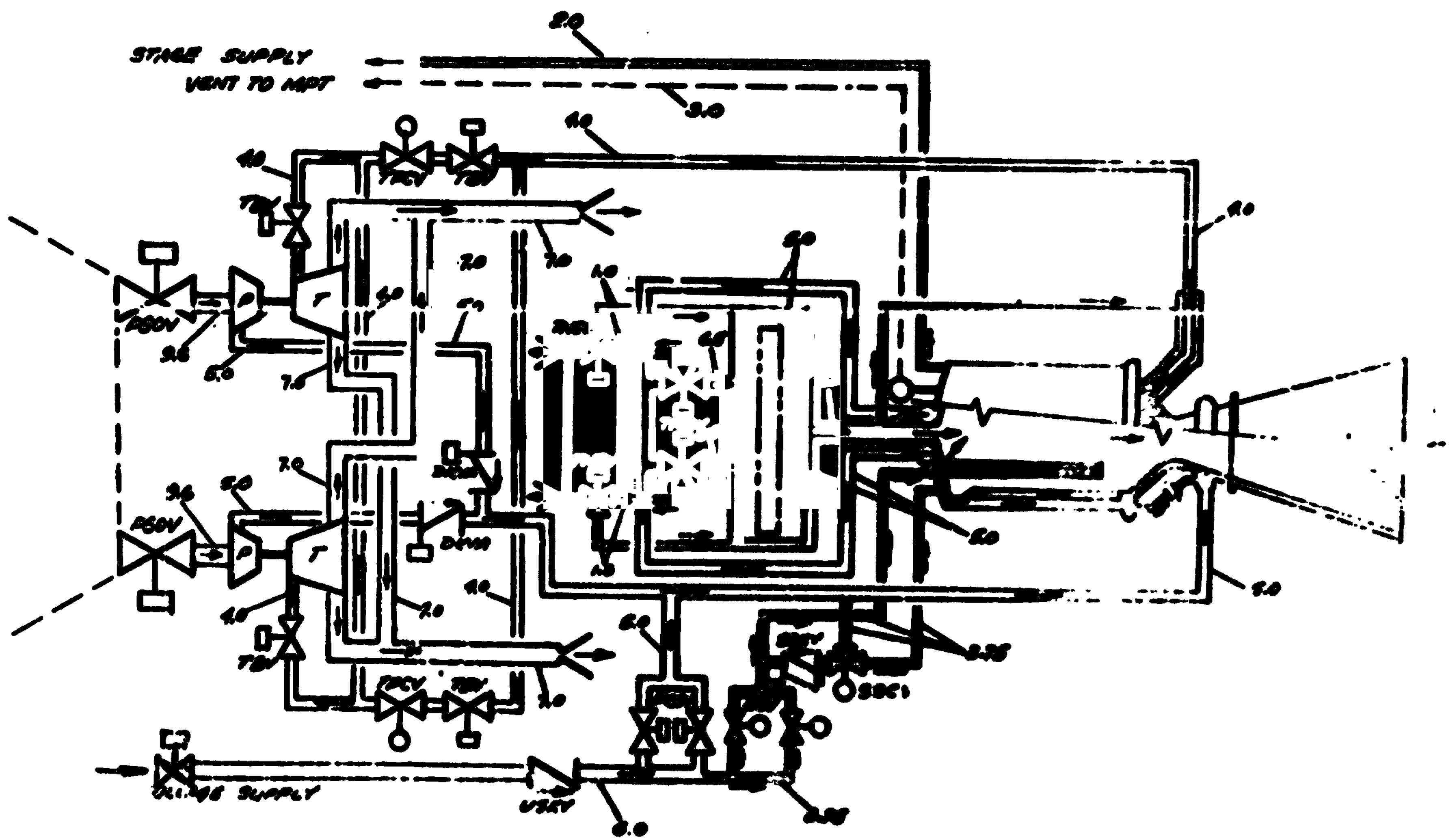
3 5 63

TANK PRESSURE ULLAGE COOLDOWN (RADIAL TN)
(SYSTEM "GAMMA")



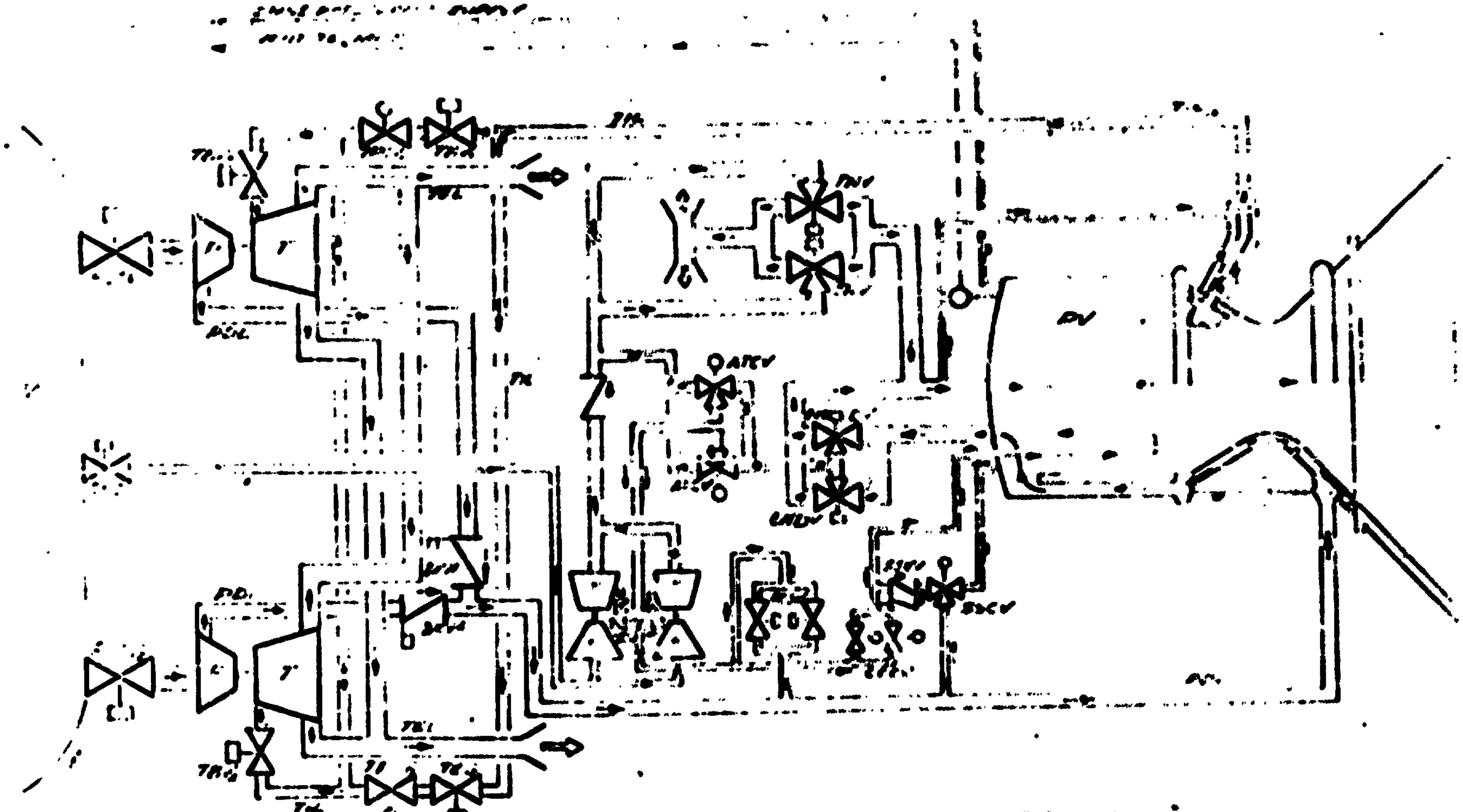
3.7

TANK PRESSURE ULLAGE COOLDOWN (AXIAL TN)
(SYSTEM "DELTA")



3.8

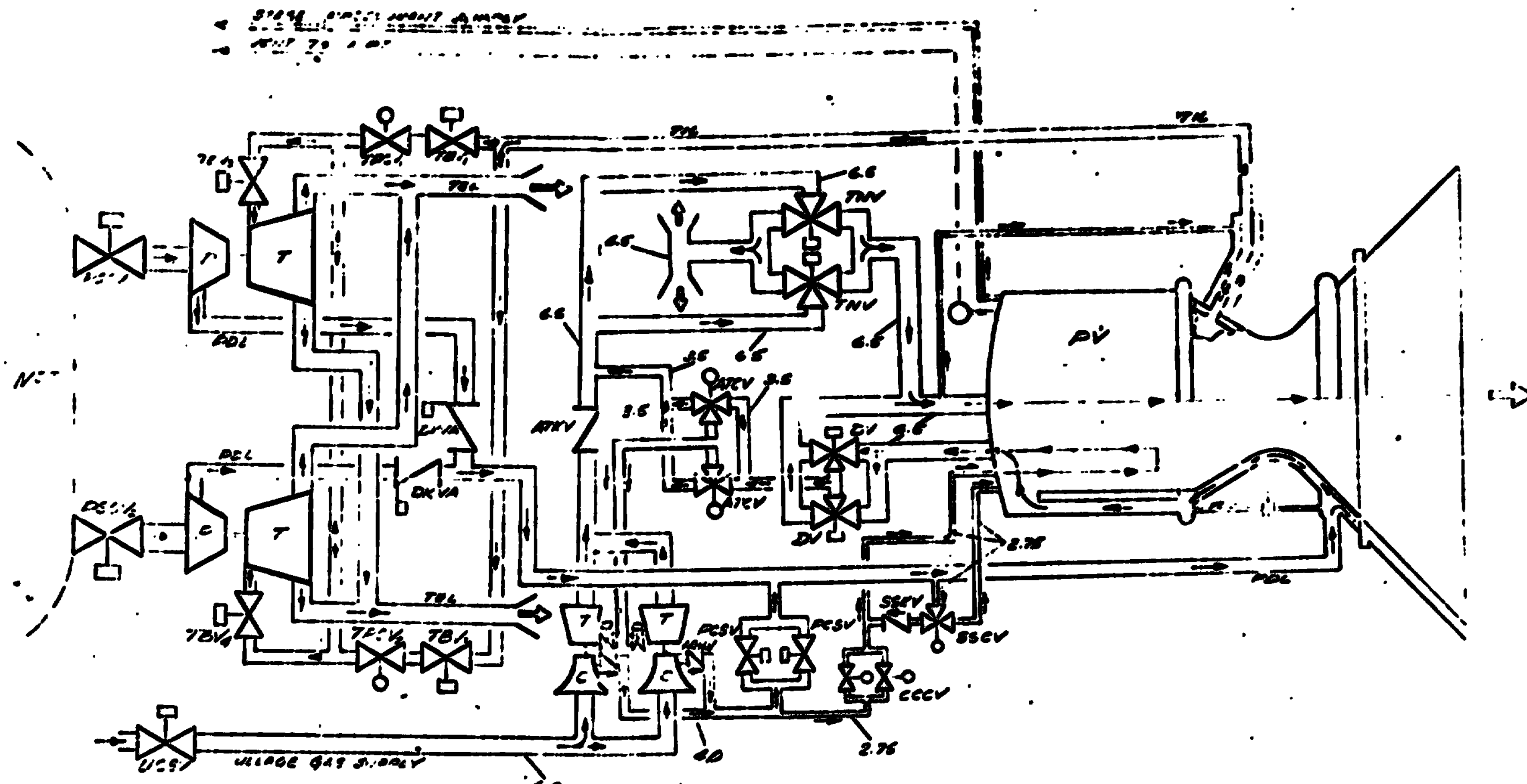
Encl (3)



LH COOLDOWN - PROPULSION SYSTEM

3.1

3.1

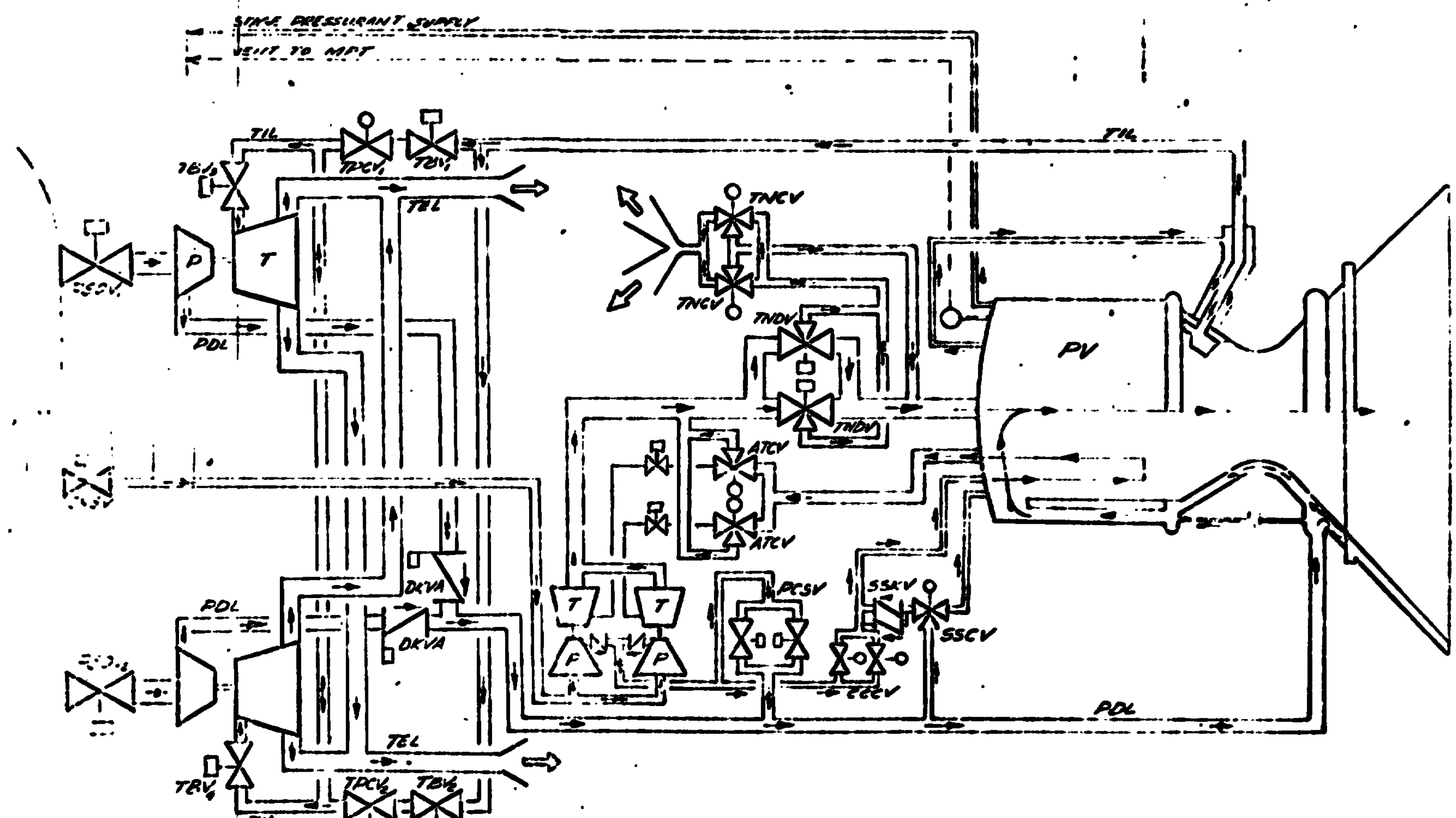


ULLAGE "C--LDOWN - TURBOCOMPRESSOR SYSTEM
(INITIAL TN) (SYSTEM "6d")

R-5-69

3.2

3.10

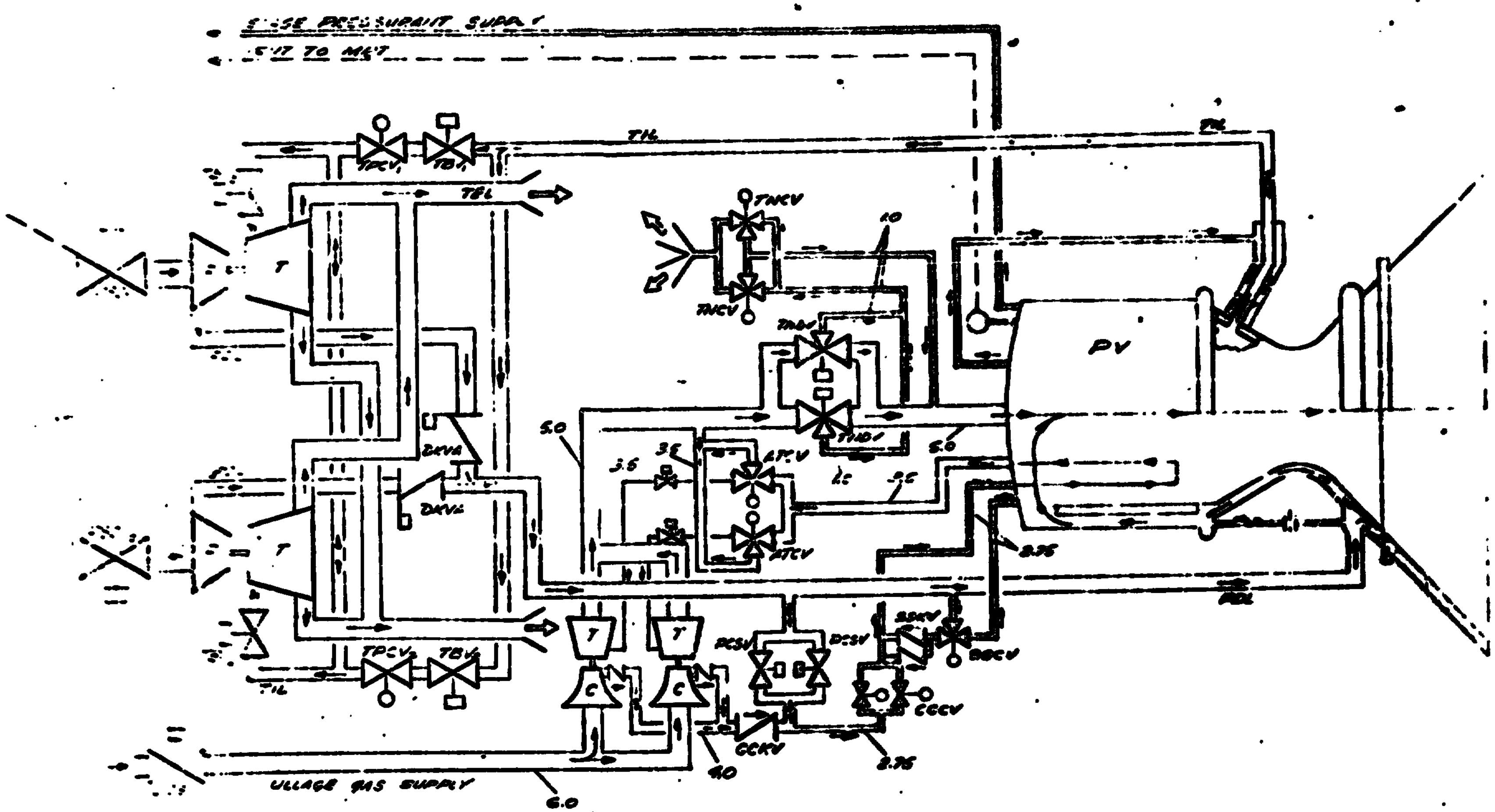


LH₂ COOLDOWN - TURBOPUMP SYSTEM
(AXIAL TN) (SYSTEM '76')

A-5-69

3.3

3.11



ULLAGE COOLDOWN-TURBOCOMPRESSOR SYSTEM
(AXIAL TN) (SYSTEM "7d")

8-5-69

3.4

CONCEPT EVENTS

Event and Cycles/Mission	ω (omega) Tank Fed-Radial Nulling-Liquid	σ (sigma) Tank Fed Axial-Liquid	γ (gamma) Tank Fed Radial-Gas	δ (delta) Tank Fed Axial-Gas	Pumped 9b Radial-Liquid	Radial 9d Gas-Compressor	Axial 7b Liquid-Pump	Axial 7d [illegible]
Thrust 8 cycles	1. CCVs reverse leak redundant with CCKV.	1. Same as omega	1. Same as omega except redundant with USKV	1. Same as gamma	1. Same as omega except redundant with APKVs or PCSVS.	1. Same as 9b	1. Same as 9b	1. Same as [illegible]
	2. CSOV forward leak impeded by higher downstream pressure.	2. Same as omega	2. UCSV forward leak same as omega	2. UCSV same as gamma CSOV	2. CNSV same as gamma CSOV	2. UCSV same as gamma CSOV	2. Same as 9b	2. Same as [illegible]
	3. TNVs must not leak to null.	3. TNDVs leak to null routes back to core through TNSVs.	3. Same as omega	3. Same as sigma	3. CNOV leak at AGCV routes back to core through TNVs	3. Same as 9b	3. Same as 9b except TNVV leak to TNCV is routed back to core.	3. Same as 7[illegible]
			4. PCSV reverse leak, redundant with USKV	4. Same as gamma	4. PCSV reverse leak redundant with APKVs or CCVs	4. Same as 9b except redundant with ACKVs or CCVs.	4. Same as 9b	4. Same as 9b
Cooldown	8 Cycles							
Coolant Supply 8 cycles	1. CSOV must open	1. Same as omega	1. UCSV must open	1. Same as gamma	1. CNSV must open	1. Same as gamma	1. Same as 9b	1. Same [illegible]
					2. Both CNDVs must close to drive turbines	2. Same as 9b	2. TNDV are normally open to core-leakage to TNCV is routed back to core.	2. Same as [illegible]
					3. At least one pump must work	3. At least one compressor must work	3. Same as 9b	3. Same as [illegible]
					4. At least one [illegible]V must open. [illegible] open ATCV must close	4. Same as 9b	4. Same as 9b	4. Same as [illegible]
					5. ATSV must close and APKV must not leak if accompanying UTPA or ABCV fails.	5. Same as 9b	5. Same as 9b	5. Same as 9[illegible]

CONCEPT EVENTS (cont.)

Event and Cycle / Mission	ω (omega) Tank Fed-Radial Nulling-Liquid 8 Cycles	σ (sigma) Tank Fed Axial-Liquid	γ (gamma) Tank Fed Radial-Gas	δ (delta) Tank Fed Axial-Gas	Pumped 9b Radial-Liquid	Radial 54 Gas-Compressor	Axial 7a Liquid-Pump	Axial 7d [illegible]
Continuous Stem Flow 8 cycles	1. At least one CCV must open 2. Both SSOVs must not leak in reverse	1. Same as omega 2. Same as omega	1. Same as omega 2. Same as omega 3. PCSVs must not leak	1. Same as omega 2. Same as omega 3. Same as gamma	1 Same as omega 2. Same as omega 3. Same as gamma	1. Same as omega 2. Same as omega 3. Same as gamma	1. Same as omega 2. Same as omega 3. Same as gamma	1. Same as omega 2. Same as omega 3. Same as gamma
Pulse Flow 130 cycles	1. At least one PSOV must open. Opened PSOV must be closed. 2. DKVA must not leak in reverse if PSOV fails to open. Assume 0 failure rate due to low pressure.	1. Same as omega 2. Same as omega	1. At least one PCSV must open. Opened PCSV must close. 2. Both DKVAs must not leak in reverse. Assume 0 failure rate due to low pressure.	1. Same as gamma 2. Same as gamma	1. Same as gamma 2. Same as gamma	1. Same as gamma 2. Same as gamma	1. Same as gamma 2. Same as gamma	1 Same as gamma 2. Same as gamma
Divert to C.D. or null 4 cycles	None	1. Fail to divert. TNCV does not effect cooling 2. Both TNCVs must close to obtain complete nulling	None	Same as sigma	None	None	1. Same as sigma 2. Same as sigma	1. Same as sigma 2. Same as sigma
4 cycles Nulling	1. Both TNCVs must close to obtain full nulling (4 cycles)	1. Both TNCVs must cycle between nulling and core cooling	Same as omega	Same as sigma	Same as omega	Same as omega	Same as sigma	Same as sigma
8 cycles Coast	1. PSOVs must not leak forward. 2. CSOV or both CCVs must not leak forward.	Same as omega	1. Same as omega 2. UCSV on both PCSVs and both CCVs must not leak forward	Same as gamma	Same as gamma	Same as gamma	Same as gamma	Same as gamma

3.14

HULL SYSTEM RELIABILITY DIAGRAMS [illegible]

[illegible] (II)

TWISTING → [PSOV_L | CSOV_L | CCV_L – CCV_L] – TNV_L – TNV_L →

ROLL DOWN → CSOV_C – CSOV_C – [CNDV_C – CCV_O | CNDV_C – CCV_O] SSKV_L – SSKV_L → a

a → [OR (1-PSOV_O) DKVA_C | PSOV_O – DKVA_C – PSOV_C | PSOV_C – DKVA_O – PSOV_C | OR (1-PSOV_C) DKVA_C] →

NULLING → TNV_N – TNV_N →

COAST → [CSOV_L | CCV_L – CCV_L] – PSOV_L – PSOV_L →

SUBSCRIPTS (TYPICAL): –

L = REVERSE LEAKAGE IN CLOSED POSITION
O = PROBABILITY OF OPENING AS REQ'D
C = PROBABILITY OF CLOSING AS REQUIRED.

CONCEPT SIGMA
(σ)

THRUSTING → [$CSOV_L$ | $CCKV_L$ | CCV_L — CCV_L] →

COOLDOWN → $CSOV_O$ - $CSOV_O$ [CCV_O | CCV_O] → a

a → $SSKV_L$ — $SSKV_L$ [$(1-PSOV_O)$ — $DKVA_L$
OR
$PSOV_O$ - $DKVA_O$ - $PSOV_L$
$PSOV_L$ - $DKVA_O$ - $PSOV_L$
OR
$(1-PSOV_L)$ — $DKVA_L$] →

NULLING → $TNSV_N$ — $TNSV_N$ →

COAST → [$CCKV_L$ | CCV_L - CCV_L] $PSOV_L$ — $PSOV_L$ →

CONCEPT GAMMA
(γ')

$$\text{THRUSTING} \rightarrow \left[\begin{array}{l} UCSV_L \\ USKV_C \\ PCSV_L - PCSV_L - CCV_L - CCV_L \end{array}\right] TNV_L - TNV_L \rightarrow$$

$$\text{COOLDOWN} \rightarrow UCSV_O - USKV_O - \left[\begin{array}{l} CCV_O \\ CCV_O \end{array}\right] - SSKV_C - SSKV_C \rightarrow a$$

$$a \rightarrow PCSV_L - PCSV_L - \left[\begin{array}{l} PCSV_O - PCSV_C \\ PCSV_O - PCSV_C \end{array}\right] - DKVA_C - DKVA_C \rightarrow$$

$$\text{NULLING} \rightarrow TNV_N - TNV_N \rightarrow$$

$$\text{COAST} \rightarrow \left[\begin{array}{l} UCSV_L \\ PCSV_L - PCSV_L - CCV_L - CCV_L \end{array}\right] PSOV_C - PSOV_C \rightarrow$$

CONCEPT DEPTH
(δ)

THRUSTING → [$UCSV_C$ / $USKV_C$ / $PSOV_C - PSOV_C - CCV_C - CCV_C$] →

COLLISION → $UCSV_0 - USKV_0$ — [CCV_0 / CCV_0] — $SSKV_C$ → a

a → $SSKV_C - PCSV_C - PCSV_C$ — [$PCSV_0 - PCSV_C$ / $PCSV_0 - PCSV_C$] → b

b → $DKVA_C - DKVA_C$ — [$TNDV_C$ / $TNDV_C$] →

NULLING → $TNSV_N - TNSV_N$ →

COAST → [$UCSV_C$ / $PCSV_C - PCSV_C - CCV_C - CCV_C$] — $PSOV_C - PSOV_C$ →

CONCEPT 5b

THRUSTING → [$CNSV_C$ / $APKV'_C$ – $APKV_C$ / $PCSV_C$ – $PCSV_C$ – CCV_C – CCV'_C] →

CIRCULATION → $CNSV_0$ – $CNDV_C$ – $CNDV'_C$ – [CCL'_0 / CCL'_C] → a

a → $SSKV'_C$ – $SSKV_C$ – $PCSV_C$ – $PCSV'_C$ – [$PCSV_0$ / $PCSV'_0$] – $DKVA_C$ → b

b → $DKVA_C$ – [(1-ATPA·ATCV) $APKV'_C$ – $ATBL'_C$ OR $APKV_0$ – $ATCV_0$ – $ATCV'_C$ – ATPA / $APKV_0$ – $ATCV_0$ – $ATCV'_C$ ATPA OR (1-ATPA·ATNV) [illegible] – $ATBL'_C$] →

NULLING → TNV_N – TNV'_N →

COAST → [$CNSV_C$ / $PCSV_C$ – $PCSV_C$ – CCV_C – CCV'_C] – $PSOV'_C$ – $PSOV_C$ →

3.144

CONCEPT 5-1

THRUSTING → UCSV_C / ACKV'_C - ACKV_C / PCSV_C - PCSV'_C - CCV_C - CCV'_C →

COOLDOWN → UCSV_O - CNDV'_C - CNDV_C - CCV_O / CCV_O → a

a → SSKV_C - SSKV_C - PCSV_C - PCSV'_C - PCSV_O / PCSV_O - DKVA_C → b

b → DKVA'_C - (1-ATCA·ATCV'_O) - APKV'_C - ATBV'_C

OR

APKV_O - ATCV_O - ATCV_C - ATCA

APKV'_C - ATCV_O - ATCV'_C - ATCA

OR

(1-ATCA·ATCV_O) - APKV_C - ATBV_C →

NULLING → TNV_H - TNV_H →

COAST → CNSV_C / PCSV_C - PCSV'_C - CCV_C - CCV_C - PSCV'_C PSCV'_C →

CONCEPT 76

$$\text{THRUSTING} \rightarrow \left[\begin{matrix} CNSV_C \\ ATKV_C - ATKV_C \\ PCSV_C - PCSV_C - CCV_C - CCV_C \end{matrix}\right] \rightarrow$$

$$\text{COOLDOWN} \rightarrow CNSV_O \left[\begin{matrix} TNDV_C \\ TNDV_C \end{matrix}\right] \left[\begin{matrix} CCV_O \\ CCV_O \end{matrix}\right] SSKV_L - SSKV_L \rightarrow a$$

$$a \rightarrow PCSV'_L - PCSV'_L \left[\begin{matrix} (1-ATPA \cdot ATCV_O) - APKV_L - ATBV_C \\ \text{OR} \\ APKV_O - ATCV'_C - ATCV'_C - ATPA \\ APKV_O - ATCV'_C - ATCV'_C - ATPA \\ (1-ATPA \cdot ATCV'_O) - APKV'_L - ATBV'_C \end{matrix}\right] \left[\begin{matrix} PCSV'_O \\ PCSV_O \end{matrix}\right] \rightarrow b$$

$$b \rightarrow DKVA_L - DKVA_L - TNDV_O - TNDV_O \longrightarrow$$

$$\text{NULLING} \rightarrow TNV_O - TNV_O \longrightarrow$$

$$\text{COAST} \rightarrow \left[\begin{matrix} CNSV_L \\ PCSV_L - PCSV_L - CCV_L - CCV_L \end{matrix}\right] PSCV_L - PSCV_L \rightarrow$$

CONCEPT 7d

THRUSTING → [UCSV'$_L$; ATKV$_L$ - ATKV'$_L$; PCSV'$_L$ - PCSV$_L$ - CCV$_L$ - CCV'$_L$] →

CORRECTION → UCSV$_0$ — [TNDV$_0$; TNDV$_L$] [CCI'$_0$; CCI'$_C$] → a

a → SSKV$_L$ - SSKV'$_L$ - PCSI'$_L$ - PCSI'$_L$ - [(1-ATCA·ATCV$_0$)-APKV$_L$-ATBI$_L$ OR APKV$_0$-AICV$_0$-ATCV$_L$-ATCA ; APKV$_0$-A V$_0$-ATCV$_L$-AICA OR (1-ATCA·ATCV$_0$)-APKV$_L$-ATBI$_0$] →

b → [PCSV$_0$; PCSI'$_0$] - DKVA$_L$ - DKVA$_L$ — TNDV'$_L$ - TNDV$_0$ →

NULLING → TNCV$_N$ - TNCV'$_N$ →

CONST → [CNSV$_L$; PCSV$_L$ - PCSV$_L$ - CCV$_L$ - CCV$_L$] - PSOV$_L$ - PSOV'$_L$ →

3.14.7

ENCL. 6

MATH MODELS

MODEL #1 SERIES*: EACH ELEMENT MUST "WORK" FOR SYSTEM SUCCESS.

DIAGRAM: $-\boxed{A_1}-\boxed{A_2}-\boxed{A_3}\text{-----}\boxed{A_i}\text{--}\rightarrow$ . . . (1)

MODEL: ONE CYCLE

$$\textcircled{R} = R_{A_1} \cdot R_{A_2} \cdot R_{A_3} \cdot \cdots R_{A_i} = \prod_{i=1}^{i} R_{A_i} \qquad (2)$$

OR IF ALL R's SAME.

$$= R_A^{i} \quad . \; . \; . \; . \quad (3)$$

MULTIPLE (n) CYCLES

$$\textcircled{R} = \left[R_{A_1} \cdot R_{A_2} \cdot R_{A_3} \cdots R_{A_i}\right]^n = \prod_{i=1}^{i} R_{A_i} \quad - - - - \quad (4)$$

OR IF ALL R's SAME.

$$= R_A^{in} \quad . \; . \; . \; . \quad (5)$$

ALTERNATELY IF VARIOUS CYCLES EFFECTIVE.

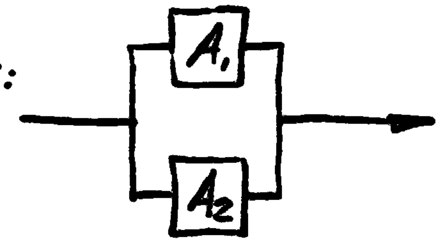
$$= R_{A_1}^{n} \cdot R_{A_2}^{m} \cdot R_{A_3}^{p} \cdots R_{A_i}^{x} \quad - - - - \quad (6)$$

* SERIES MODEL IS USED TO COMBINE SUB-COMPONENTS, SUBSYSTEMS AND GROUPS TO CALCULATE SYSTEM RELIABILITY.

MODEL #2

PARALLEL: EITHER OR BOTH ELEMENTS MUST WORK. ACTIVE REDUNDANCY.

DIAGRAM:



. . . . (1)

MODEL: ONE CYCLE

$$R = 1-(1-R_{A_1})(1-R_{A_2}) \quad \text{OR } A_1 = A_2 \cdots (2)$$

$$= 1-(1-R_A)^2 \cdots (3)$$

$$\text{OR } = R_A^2 + 2R_A(1-R_A) \cdots (4)$$

MULTIPLE (n) CYCLES

$$R = 1-\left[(1-R_{A_1}^n)\cdot(1-R_{A_2}^n)\right] = 1-(1-R_A^n)^2 \cdots (5)$$

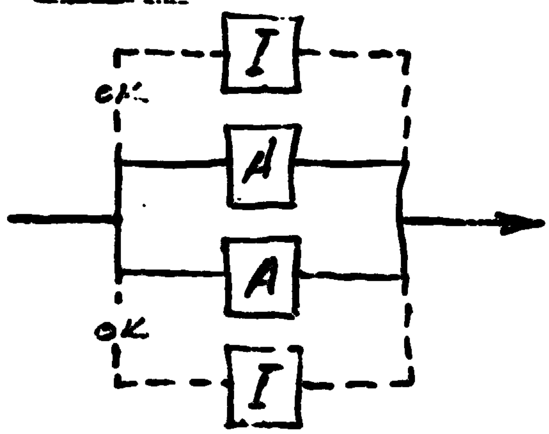
$$\text{OR } = R_A^{2n} + 2R_A^n(1-R_A^n) \cdots (6)$$

~~6.2~~ 3.14.9

MODEL

#3 PARALLEL STANDBY REDUNDANCY
FAILURE IN ONE LEG WILL BE ISOLATED.

DIAGRAM:



MODEL: ONE CYCLE

$$ⓡ = R_A^2 + 2 R_A R_I (1-R_A) \text{ - - - - - - - } ①$$

MULTIPLE (n) CYCLES

$$ⓡ = R_A^{2n} + 2 R_A^n R_I (1-R_A^n)^* \text{ - - - - - - } ②$$

* WHERE $\underline{A}$ IS THE ACTIVE LEG AND (1-A) IS THE FAILED LEG AND I IS THE ISOLATION "NETWORK".

3.14.10

[illegible]

[illegible]

COMP	NORMAL POSITION *	MODE OF FAILURE	RELIABILITY (ONE CYCLE)	FAILURE RATE (fpm)	REMARKS
[illegible]	OPEN	REVERSE LEAK	[illegible]	40	
AT-V	OPEN	REVERSE LEAK	[illegible]	[illegible]	
[illegible]	[illegible]	FAIL TO CONTROL	[illegible]	[illegible]	
APRV	OPEN	REVERSE LEAK	.9460	[illegible]	
[illegible]	OPEN	FAIL TO CLOSE	[illegible]	[illegible]	
[illegible]	n/a	NO OUTPUT	.9₃723	277	
[illegible]	none	FAIL TO CONTROL	.9₃831	[illegible]	
ATPA	n/a	NO OUTPUT	.9₃656	344	
CCKV	[illegible]	REVERSE LEAK	[illegible]	40	
[illegible]	CLOSED	FAIL TO CONTROL	.9₃831	164	
CONTROL	n/a	FAIL TO CONTROL			
[illegible]		- AXIAL [illegible]	.9₃750	250	
		- [illegible]	.9₃750	250	
		- RADIAL [illegible]	.9475	[illegible]	
[illegible]	THROTTLING	FAIL TO DIVERT	.9₃506	[illegible]	
[illegible]	CLOSED	FAIL TO OPEN.	[illegible]	164	
[illegible]	[illegible]	FAIL TO [illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	REVERSE LEAK.	[illegible]	40	
		FAIL TO CLOSE	.9₃856	144	
[illegible]	[illegible]	[illegible]	.9₃856	[illegible]	
[illegible]	[illegible]	FAIL TO OPEN	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible] 831	[illegible]	
[illegible]	OPEN	[illegible]	[illegible]	40	
[illegible]	[illegible]	FAIL TO CLOSE	[illegible]	[illegible]	
	[illegible]	[illegible] OPEN	.9₃856	144	
[illegible]	[illegible]	FAIL TO [illegible]	.9₃831	164	
[illegible]	THROTTLING	FAIL TO DIVERT	.9₃[illegible]	164	
[illegible]	[illegible]	REVERSE LEAK	[illegible]	[illegible]	
[illegible]	[illegible]	FAIL TO [illegible]	.9₃831	[illegible]	
[illegible]	THROTTLING	[illegible]	[illegible]	[illegible]	
[illegible]	CLOSED	FAIL TO OPEN	[illegible]	[illegible]	
[illegible]	[illegible]	REVERSE LEAK	[illegible]	40	
[illegible]	[illegible]	[illegible] LEAK	.9475	[illegible]	
[illegible]	[illegible]	REVERSE LEAK	.9475	25	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible] LEAK	.9475	[illegible]	
[illegible]	CLOSED	[illegible] LEAK	[illegible]	25	
[illegible]	CLOSED	REVERSE LEAK	[illegible]	[illegible]	
[illegible]		[illegible]	1.00	0	
		16.11	3.79.11		

RELIABILITY ALLOCATION MATRIX

MISSION	ω omega LIQUID PRESS RADIAL	σ sigma LIQUID PRESS AXIAL	γ gamma GAS PRESS RADIAL	δ delta GAS PRESS AXIAL
THRUSTING	8 ~ *1 $.9_475$ 1 $.9_475$ 8 $.9_460$ $.9_475$	8~*8 $.9_460$ $.9_475$	8~ *1 $.9_475$ 1 $.9_475$ 8 $.9_460$ $.9_475$	8~*8 [illegible] [illegible]75
THRUSTING REL	$.9_3600$	$.9_74$	$.9_3600$	$.9_74$
COOLDOWN	8~ *1 $.9_3816$ 3 $.9_3264$ 3 $.9_3831$ 1 $.9_460$ 1 $.9_460$ 130~ 8 $.9_3816$ 1.0	8~ 1 $.9_3856$ 3 $.9_3831$ [illegible] 1 $.9_460$ 3 $.9_3856$ 130~ 8 [illegible] 1.0	8~ 1 $.9_3831$ 1 [illegible] 1 [illegible] [illegible] 1 [illegible] 1 $.9_381$[illegible] 130 [illegible]	8~ 1 [illegible] 1 [illegible] 1 [illegible] 1 [illegible] 1 [illegible] 1 [illegible] 3 [illegible] 130 [illegible]
	$.9_27295$	$.9_27330$	$.9_27146$	$.9_27146$
NULL	4~*1 $.9_3856$ 1 $.9_3856$	4~ 1 $.9_3831$ 1 $.9_3831$	4~ 1 $.9_3856$ 1 $.9_3856$	4~ 1 [illegible] 1 $.9_3831$
	$.9_28449$	$.9_28649$	$.9_28841$	[illegible]
CONST	8~*3 $.9_450$ 1 $.9_475$ 1 $.9_475$	8~ 3 $.9_450$ 1 $.9_475$ 1 $.9_475$	8~ 3 [illegible] 1 $.9_475$ 1 $.9_475$	8~ [illegible] 1 [illegible] 1 [illegible]
	$.9_3600$	$.9_3600$	$.9_3577$	$.9_357$[illegible]
RELIABILITY	.995351	.995554	.995301	.99534[illegible]

~~7.1~~ 3.1412

PHASE	6b LIQUID PUMP RADIAL	5d GAS COMPR RADIAL	7b LIQUID PUMP AXIAL	7d GAS COMPR AXIAL
THRUSTING	9N [illegible] .[illegible] .9₄75	8 N's .9₄60 .9₄75	8N [illegible] .9₄60 .9₄75	8N #8 .9₄60 .9₄75
REL.	[redacted] .9₂4	.9₂4	.9₂4	.9₂4
CRUISING	3N 1.9₃[illegible] 1.9₃556 1.9₃[illegible] 8.9₃[illegible] .9₃7[illegible] 1.9₄60 1.9₄60 3.9₃831 1.9₄75 1.9₄75 130N 3.9₃556	9N 1.9₃556 1.9₃556 1.9₃556 8.9₃[illegible] .9₃577 1.9₄6 1.9₄[illegible] [illegible] 1.9₄75 1.9₄75 13N 3.9₃[illegible]	8N 1.9₃556 8.9₃4[illegible] .9₃777 3.9₃531 1.9₄60 1.9₄60 1.9₄75 1.9₄75 130N 3.9₃556 8N 1.9₃556 1.9₃556	8N 1.9₃[illegible] 8.9₃456 .9₃517 3.9₃[illegible]1 1.9₄60 1.9₄60 1.9₄75 1.9₄75 130N 3.9₃556 8N [illegible] .9₂556
REL	.9₂4847	.9₂4837	.9₂4948	.9₂4537
NULL	4N 1.9₃556 .9₂556	4N 1.9₃556 1.9₃[illegible]	4N 1.9₂831 [illegible]	4N 1.9₂[illegible]1 [illegible]
REL	.9₂9947	.9₂[illegible]	.9₂[illegible]	.9₂[illegible]
COAST	8N 3.9₄[illegible] 1.9₄75 1.9₄75	8N 3.[illegible] 1.9₄75 1.9₄75	8N 3.[illegible] 1.[illegible] 1.[illegible]	8N 3.[illegible] 1.[illegible] 1.[illegible]
REL	.9₃577	.9₃577	.9₃577	.9₃577
RELIABILITY	.993303	.993293	.994250	.994237

~~7.4~~ 3.14.13

MEMORANDUM

TO:	R. H. Coppo/S. J. Komjathy (3 ea)	22 July 1969 7850:M0219
FROM:	F. C. Valls	
SUBJECT:	Comparative Preliminary Design Reliability Evaluation of a "U" Tube (1136367) versus an "Oval" Tube (1136081) Nozzle Skirt	
COPIES TO:	W. J. Bronner, W.M. Bryan, F. E. Porter, J. H. Ramsthaler, L. A. Shurley, E. J. West, R. D. Zonge	
ENCLOSURE: (To addressees only)	(1) Summary of the Comparative Failure Modes (2) "U" Tube Nozzle Component Mechanism of Failure Analysis (3) "Oval" Tube Nozzle Component Mechanism of Failure Analysis	

Enclosures listed above represent a completed preliminary comparative component mechanism of failure analysis of the "U tube, steel jacketed" versus the "oval (O) tube bundle, band reinforced" nozzle skirt concepts.

From the summation of the mechanism failure rates for all the elements of each concept participating in each mode of failure, one must predict that the tube bundle is a more reliable design than the jacketed design (predicted $.9_4 70$ vs $.9_3 663$).

Reviewing the synthesis of the comparative reliability of the "U" tube and the "oval" tube, it is interesting to postulate(in terms of the designs failure rates (failures/million cycles) and component failure modes) what specific inferences can be made from the quantitative evaluation. Accordingly, the significant recorded failure rates for the "U" and the "oval" configurations are observed, as:

1. (202 vs 77) for the end caps.

2. (135 vs 53) for the nozzle tube designs.

The summation of the failure rates of the mechanisms, constituting each of the three principal modes of failure, also respectively for each tube concept, are:

1. To transmit axial thrust (41 vs 5).

2. To resist internal pressure (9 vs 26).

3. To conduct coolant (157 vs 99).

3.15

R. H. Coppo/S. J. Komjathy

22 July 1969
7850:M0219

Considering first the R_D justifications, it can be thus predicted that the jacketed nozzle design will have more problems from longitudinal differential expansion of the "U" tubes and support, as well as, from the differential radial expansions of the flanges, jacket and tubes. Secondly, the R_q factor for the jacketed design can be substantially reduced, by employing more sophisticated methods of preventing or detecting potential cyclical damage.

This preliminary reliability engineering analysis has been prepared for a final review with the design and quality assurance engineers. During the preparation of this report several design modifications, as well as quality assurance techniques, have been proposed and are presently under consideration. These should reduce the failure rate of the jacket design considerably and together with other considerations make the design more attractive.

F. C. Valls

F. C. Valls
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE

3.16

MEMORANDUM

TO: A. V. Lundback

DATE: 31 July 1969
7850:M0234

FROM: J. H. Morison

SUBJECT: Reliability Critique of PSS Schematic (Dwg. No. 1136354)

COPIES TO: J. H. Altseimer, J. J. Beereboom, B. Mandell, I. L. Odgers, J. H. Ramsthaler, 7850 Personnel

REFERENCE: (a) Memo 7770:M:6138, dtd 2 Jul 69, A. V. Lundback to C. R. Snyder, Subject: Minutes of Meeting to Discuss Integrated PSS Trade Study and System Design Report

In response to Reference (a) a preliminary reliability review was completed for the subject PSS. Two potential problem areas with regard to reliability became apparent. They are as follows:

a. Both PSOV's operate off of a common PSS isolation valve pair. This tends to negate the redundancy of the twin TPA systems because failure of both isolation valves can shut down both TPA legs. It is recommended that individual PSS isolation valve pairs and lines be used to supply each PSOV.

b. It should be noted that both TBVs and the TPCV of each TPA assembly operate off one PSS isolation valve pair. If both isolation valves in a leg fail to open (e.g., SSV-29 and SSV-28) at the beginning of a thrust period, the TBVs (TBV_1 and TBV_3), will be left open and the TPCV ($TPCV_1$) will be left closed. Assuming that the primary function the fast-closing TBVs is to isolate potentially-destructive TPA failures, both TPAs can be operated by the surviving TPCV ($TPCV_2$) but no means are available for isolating the orphaned TPA (TPA_1) in the event it fails. The failure of the isolation valves would therefore probably be cause for aborting the mission. It is recommended that some means of isolating a TPA be provided in the event of a failure of a corresponding isolation valve pair, or provision be made for separate isolation valves for TBV_3 and TBV_4.

J. H. Morison

J. H. Morison
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

3.17

MEMORANDUM

TO: R. D. Huffman

DATE: 1 August 1969
7850:M0235

FROM: L. P. Burke

SUBJECT: Preliminary Reliability Review of Department 7820 Turbine Drive Fluid Control Evaluation

COPIES TO: J. J. Beereboom, W. M. Bryan, V. M. H. Chang, N. F. Wessinger, H. Musgrove, J. H. Ramsthaler, E. A. Sheridan, 7850 Personnel

REFERENCE: (a) Feasibility Evaluation of Alternate Pressure Control Concepts, N. F. Wessinger, dated July 1969 (Not published, preliminary)

Reference (a) evaluated several methods of controlling turbine power and concluded that the use of binary or analogue valves in parallel with a fixed orifice may result in a more reliable and simpler control system than the single analogue valve used for the present reference engine design.

The detailed circuitry that would be required to control the proposed orifice/valve(s) system has not been designed. Therefore, evaluation of which system may be most reliable will be one of conjecture at this time.

Conclusions

The operation of the parallel valve(s) is understood to be required in addition to the orifice during engine start and cooldown. As a result, the reliability of the proposed parallel orifice/valve(s) systems will be less than the reliability of the reference engine analogue valve turbine power control during engine start and cooldown.

The degradation in reliability derives from the orifice element, as the success of the turbine power system is dependent upon the successful operation of both the orifice and parallel valve(s) system.

The simplicity and potentially greater reliability of a digital/multivibrator type control system as compared to an analogue system is recognized, but this gain may be offset by the reliability product of multiple parallel binary valves. This is particularly so if all the parallel valves must be opened or closed (no failures allowed) for the system to correctly operate.

In all of the parallel orifice/valve(s) systems proposed, no means have been shown that allow isolation of a valve(s) failure. Should a parallel valve failure occur, loss of control over a subsequent startup would occur.

Recommendations

Single or multiple valves parallel to an orifice turbine power control is not recommended because of system reliability degradation during engine start and cooldown.

Should an orifice system prove advantageous for controlling steady state operation, a separate orifice isolation and start and shutdown system is recommended, with some means of TPCV redundancy and isolation.

Detailing of control circuit blocks is recommended to allow a reliability analysis of this portion of the turbine power control system.

L. P. Burke
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

3.17

MEMORANDUM

TO:	R. B. Wright	DATE: 6 August 1969 7850:M0239
FROM:	E. B. Cleveland	
SUBJECT:	Reliability Evaluation of Diluent Supply and Bolt Coolant Concepts - Trade Study 006	
COPIES TO:	W. M. Bryan, J. J. Beereboom, D. S. Duncan, J. H. Ramsthaler, L. A. Shurley, J. L. Watkins, E. J. West, 7850 Personnel	
REFERENCE:	(a) Memo 7770:M6139, dtd 7 July 1969, L. D. Johnson to J. M. Klacking, Subject: Diluent Control Valve	
ENCLOSURE:	(1) Concepts Layout 1136744 (2) Reliability Evaluation Chart	

The three concepts for diluent supply and bolt coolant for Trade Study 006 shown in Enclosure (1) have been evaluated as to their relative reliability.

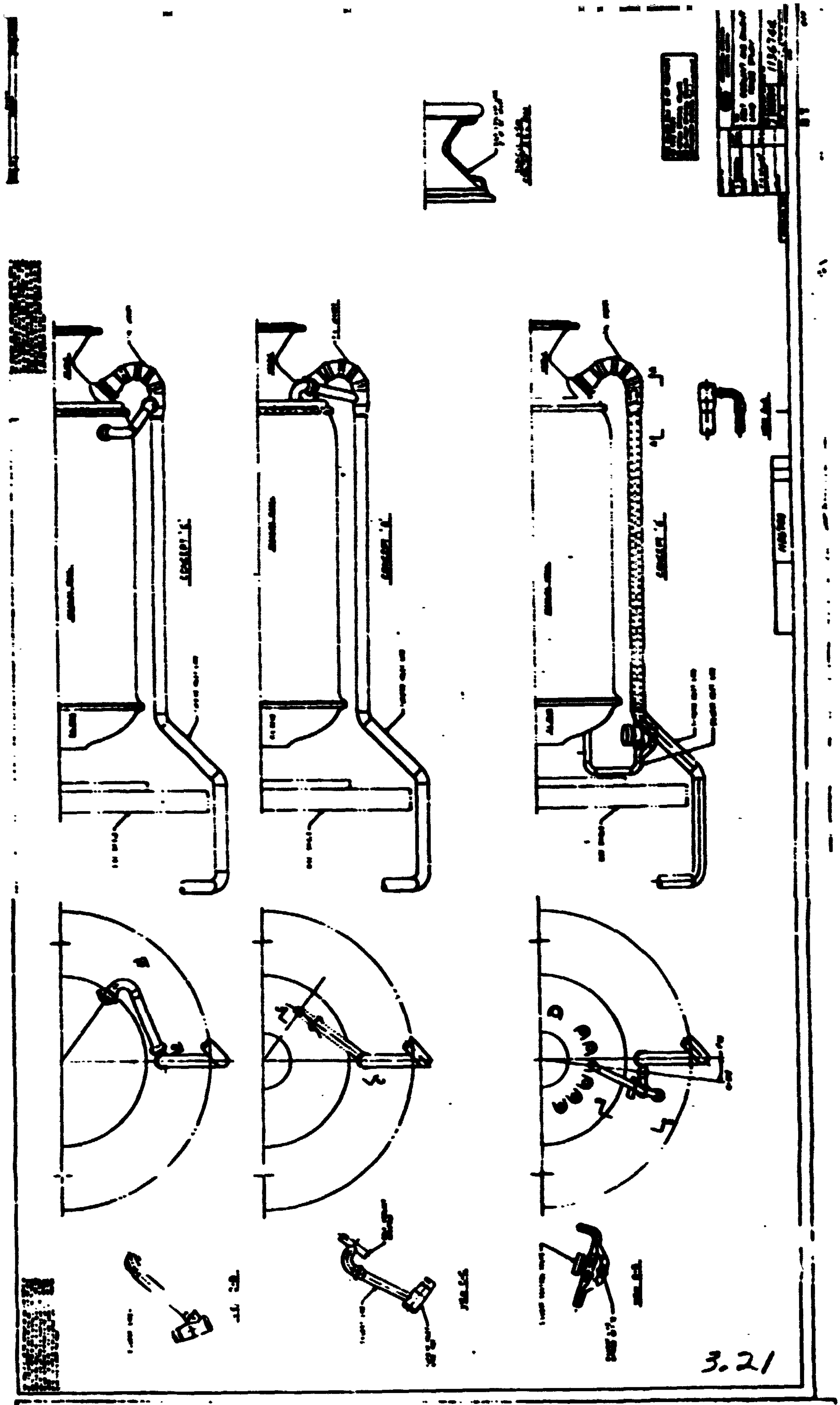
The numerical ratings, Enclosure (2), show no significant difference between Concepts B and C. Both feature short lines that should resist vibration equally well. Concept B permits deletion of the two Bolt Coolant lines and their possible failure modes, however, flow of the diluent to the hot gas bleed port is in series with the small passages in the bolts. Although not evaluated in detail it may be possible to have reduced diluent flow because of restrictions in some of the bolts. The reduced flow may not result in failure of the bolts but may require a reduction in engine power.

Concept C requires a port in the pressure vessel in a region of high stress which would be expected to reduce reliability.

The evaluation indicates that Concept A would be expected to have the lowest reliability of the three. This is primarily because of the greater number of weld joints and the increased susceptibility to failure from vibration-induced stresses of this long line. To simplify the evaluation and based on the recommendations of Reference (a), the DCV has not been included. The DCV would only further reduce the relative reliability of Concept A.

E. B. Cleveland
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

3.20



3.21

RELIABILITY EVALUATION OF: DILUENT SUPPLY AND BOLT COOLANT CONCEPTS - TRADE STUDY 006

SYSTEM FUNCTIONS:

Diluent Supply - supply diluent to the TIL jacket at the proper temperature, pressure and wt. flow, without adversely effecting engine operation.

Bolt Coolant - supply coolant to the PV/aft closure bolts so as to prevent excessive heating of the joint, and without adversely effecting engine operation.

REFERENCE ENGINE - 1136339

				Reverse Bolt Coolant Flow		Forward Bolt Coolant Flow				
				Concept B per 1136744 Nozzle Flange Torus to TIL Diluent Sup.		Concept A per 1136744 PV Dome to TIL Diluent Sup.		Concept C per 1136744 PV Reflector to TIL Diluent Sup.		
Item	Subsystem	Failure Mode	Mechanism of Failure	Effect	*Rating	Effect	*Rating	Effect	*Rating	Remarks
1.	Diluent Supply	a) Inadequate flow conditions	1) Leakage at flange seals (all leakage assumed to be less than total loss of flow).	Hot gas to turbine will be at high temp. Require reduction engine power. (1 joint)	1.0 1.0 -	(Same as B) (2 joints)	- 0 0	(Same as B) (2 joints)	- 0 1.0	Should be less chance of leakage in C vs. A because vibration loads will be less in shorter line of C.
			2) Leakage at weld joints.	(Same as above) (6 joints)	0.5 0.5 -	(Same as B) (11 joints)	0 - 0	(Same as B) (9 joints)	- 0 0.5	1.a.2 & 3 both have a low probability of occurring.
			3) Restriction in diluent line.	(Same as 1. above)	0.5 0.5 -	(Same as B)	0 - 0	(Same as B)	- 0 0.5	
		b) No flow	1) Structural failure of PV or dome port.	Not possible in this concept because diluent is not taken from PV or dome.	0.5 0.5 -	Engine failure	0 - 0.5	Engine failure	- 0 0	Port in concept C is in a region of higher stress.

RELIABILITY EVALUATION OF: DILUENT SUPPLY AND BOLT COOLANT CONCEPTS - TRADE STUDY [illegible]

Item	Subsystem	Failure Mode	Mechanism of Failure	Reverse Bolt Coolant Flow Concept B per 1136744 Nozzle Flange Torus to TIL Diluent Sup. Effect	*Rating	Forward Bolt Coolant Flow Concept A per 1136744 PV Dome to TIL Diluent Sup. Effect	*Rating	Forward Bolt Coolant Flow Concept C per 1136744 PV Reflector to TIL Diluent Sup. Effect	*Rating	Remarks
			2) Structural failure of diluent line from excessive vibration loads (either weld, bellows, or joint failure).	No coolant available to cool bleed port. Shut engine down.	1.0 0 -	(Same as B)	0 - -	(Same as B)	- 1.0 1.0	
2.	Bolt Coolant	a) Inadequate flow	1) Leakage at bolt seals.	Amount of diluent to bleed port is reduced. Reduce engine power level. Bolts will have less flow around the shank and may overheat.	0 0 -	Bolts will have less flow of coolant up thru the shank and may overheat.	1 - 0.5	(Same as A)	- 1 0.5	Does not seem good to have diluent flow thru small holes before getting to the bleed port as require in B.
			2) Restriction of bolt coolant passages.	Reduces amount of diluent flow to the bleed port.	0 0 -	Bolt temp. will increase.	1 - 0.5	Bolt temp. will increase.	- 1 0.5	Assumes that several non-adjacent bolts can be restricted without resulting in structural failure of the joint.
			3) Structural failure of bolt coolant lines or torus.	Diluent flow to bleed port will stop. Shutdown engine. Hot bleed gas will flow out thru rupture.	0.5 0.5 -	Bolt coolant stops. Plenum gases will flow thru bolts and out thru rupture. Shut engine down.	0 - 0.5	(Same as A)	- 0 0.5	
			SUMMATION OF RATINGS		7.0		4.0		7.5	

* Normal rating is 1.0. Lower prob. of occurrence is 0.5.

MEMORANDUM

TO: L. D. Johnson

DATE: 3 September 1969
7850:M0267

FROM: W. M. Bryan

SUBJECT: Reliability Analysis in Support of Trade Study Number 007

COPIES TO: J. J. Beereboom, V. M. Chang, A. D. Cornell, D. S. Duncan, J. M. Klacking, E. V. Krivanic, C. F. Leyse, B. Mandell, I. L. Odgers, D. E. Price, W. O. Wetmore
NTO: W. H. Bushnell

ENCLOSURES: (1) WANL Control Drum Trade Study Reliability Assumptions
(2) Preliminary System Reliability Analysis

A preliminary review has been made of the reliability analysis presented by WANL in support of the Reactor Controls Concept Trade Study (701).

It is concluded the WANL analysis is in error. They computed reliability two ways, the first analysis assumed mission failure occurred if any of the drums failed, and the second analysis assumed one drum failed at launch, and the mission was continued with a degraded reliability on the core due to temperature scalloping.

They then indicated there was a slight reliability advantage for the lower number of drums for case #1, and a large reliability advantage for the higher number of drums for case #2. They recommended NERVA have 36 drums saying that case #2 was the one which must be considered since the NPRD says no one failure is permissable.

Their calculation technique on case #1 is valid but their calculation is in error on case #2 and their interpretation of the NPRD for reliability calculations is also wrong. The NPRD says: "In particular, maximum effort should be placed on a design which eliminates single failures or credible combinations of errors and/or failures which endanger the completion of the mission flight crew, launch crew or the general public". WANL interpreted this to mean reliability should be computed given the failure has occurred. This is, of course, ridiculous because it would then be necessary to compute reliability with one of everything failed.

The equation for case #2, calculating reliability with a one out compatibility, did not consider that the need for operating with the core in a degraded condition only occurs given that a drum has already failed. Therefore, the probability that the mission will succeed is enhanced by the one out capability not severely degraded as WANL concluded by failing a drum at launch. The judgement in their model is also felt to be poor for the following reasons:

a. They considered an equal probability of fail in and fail out with no consideration of fail in place. Fail "in place" and fail "in" have a minor effect on core reliability compared to fail "out" which degrades it substantially. By designing the drums to fail in place or in the reliability degradation associated with a failure could be minimized.

3.24

b. They did not consider failure rates associated with I&C and the pneumatic supply systems which increase as the number of drums increase.

c. No reliability decrements were considered for changes in reflector and dome reliability associated with changes in the number of drums.

d. No consideration was given to multiple drum failures which might randomly occur or could result from items common to banks of drums such as the P.S.S.

e. They did not give sufficient consideration to the fact that the failure rates derived were very subjective and therefore, they should have conducted sensitivity studies to determine if the advantage for the various concepts changes if the failure rates are indeed in error.

A few preliminary studies have been made at AGC using the WANL-identified failure modes to determine the sensitivity of the drum system reliability to errors in the failure rate estimates. The model used for the study is shown in Enclosure (1). This model considers the combined effect of the total system success and system success if one drum fails in the in, or out position. The start point failure rates represent those utilized in WANL's study.

Enclosure (2) shows the drum system reliability as a function of actuator failure rate at three levels of I&C reliability. In all cases except at high I&C reliability and high actuator failure rate the lower number of drums is the more reliable. In the exception case the 18 drum system is slightly more reliable than the twelve, but in all cases the 36 drum system is the poorest.

Enclosure (3) shows an increase in the spread between the three system reliability values when a single drum failure is considered to have occurred at mid-mission instead of at launch and that fail "in place" is added as a drum failure mode. (For simplicity in this preliminary analysis, each of the three failure modes was considered equally likely.) Again the reliability values are calculated as a function of actuator failure rate to determine the sensitivity of the concept comparison. For all cases, the lower number of drums is the more reliable.

Enclosure (4) lists the assumptions made in WANL's reliability analysis which resulted in the recommendation for the 36 drum concept. Assumption number (1) was the key item that resulted in a "sub-optimization" of reliability given that the reactor was in a failed state. However, most of the other assumptions seem also to favor the 36 drum concept. It is recommended that further analyses be made by WANL of the various reactor control concepts considering total system reliability and reliability sensitivity analyses to test the resultant recommendations against critical parameters and assumptions. Critical parameters recommended for sensitivity analysis include the following:

a. Actuator failure rate.

b. Reactor failure rate (both in success and failed state).

c. Fail position of actuators.

3.25

d. Increased complexity associated with 36 drum design.

e. Effect of the failed state with reduced drum span.

f. Reliability degradation during coast.

W. M. Bryan

W. M. Bryan, Supervisor
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Bryan 9/3/69
CLASSIFYING OFFICER DATE

3.26

NSS CONTROL DRUM SYSTEM MATH MODEL (N DRUMS)

$$R_{N\ ACT.\ SYSTEM} = R_{E-N} \cdot R_{ACT}^{N} \cdot R_{SSCV} \cdot R_{CORE-S}$$

$$+ R_{E-N} \cdot N\,(1-R_{ACT-IN}) \cdot R_{ACT}^{N-1} \cdot R_{CORE-IN}$$

$$+ R_{E-N} \cdot N \cdot R_{ACT-IN}\,(1-R_{ACT-OUT})\ R_{ACT}^{N-1} \cdot R_{CORE-OUT}$$

$R_{N\ ACT.\ SYSTEM}$ = Probability an N actuator system survives allowing one failure

R_{E-N} = Rel. of electronic controls for N actuator system

R_{ACT} = Rel. of actuator = $R_{ACT-IN} \times R_{ACT-OUT}$

R_{ACT-IN} = Probability one actuator does not fail in

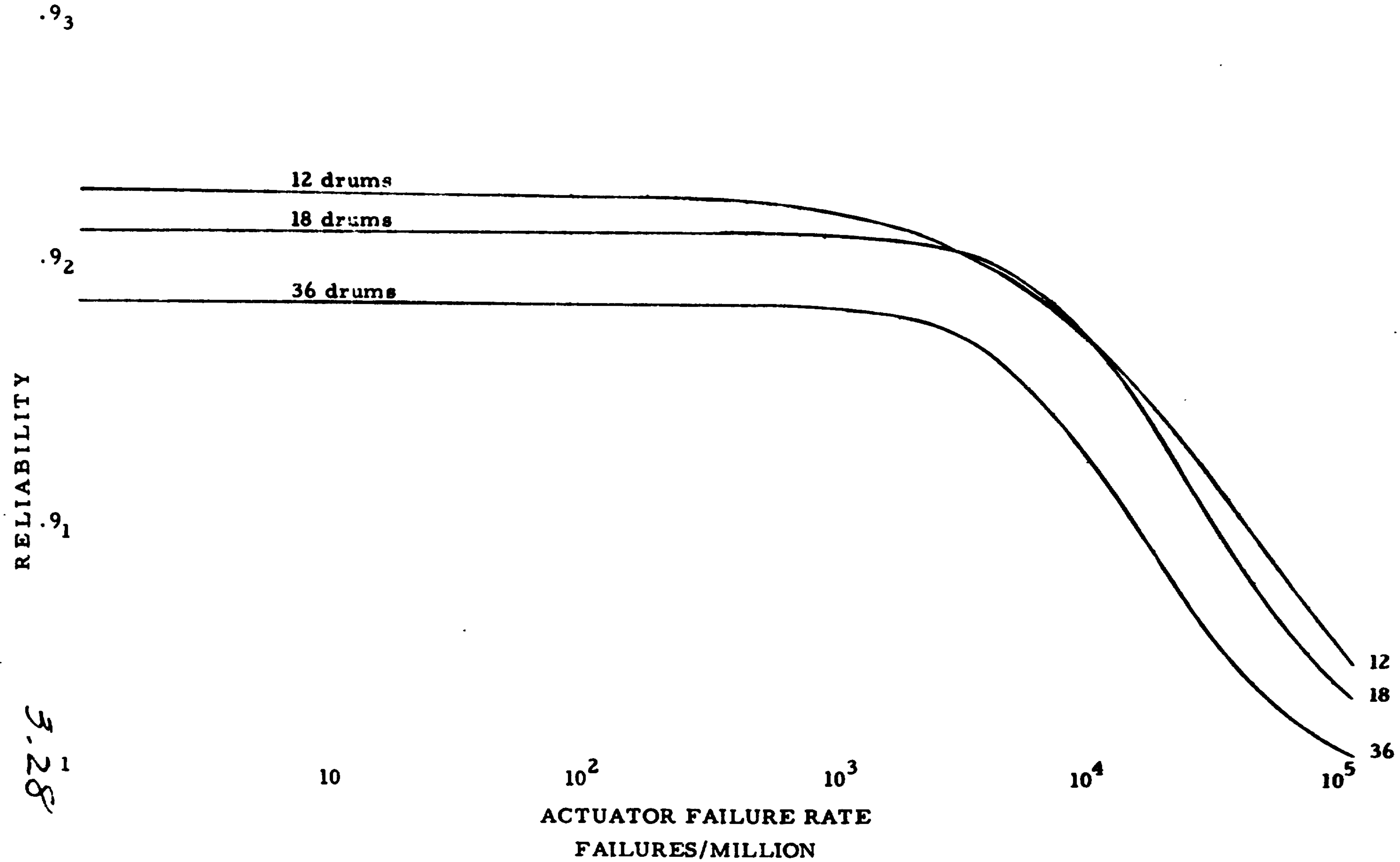
$R_{ACT-OUT}$ = Probability one actuator does not fail out

R_{CORE-S} = Reliability of core with N actuators correctly positioned

$R_{CORE-IN}$ = Reliability of core given one actuator failed in

$R_{CORE-OUT}$ = Reliability of core given one actuator failed out

Enclosure (2)
7850:M0267



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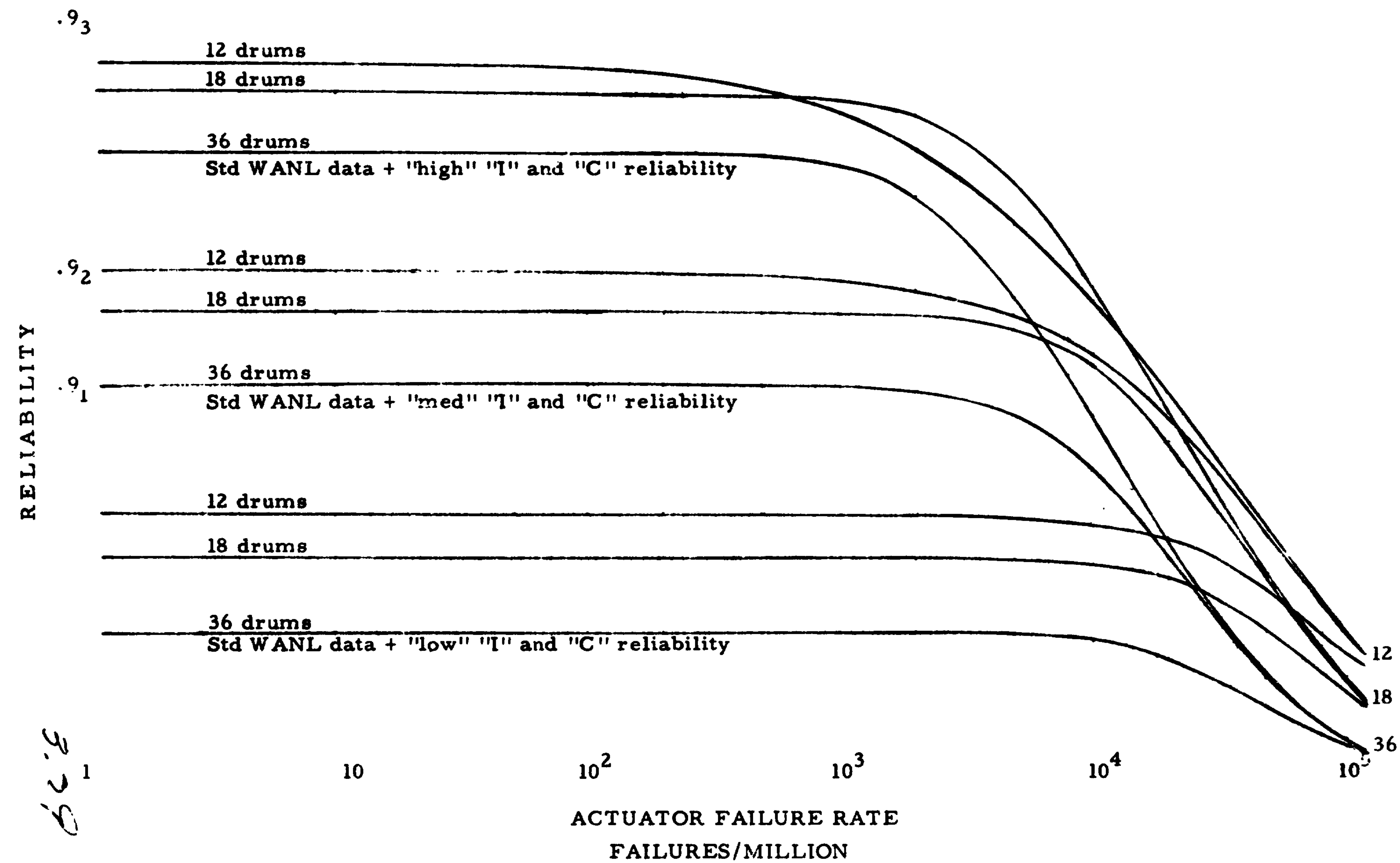

RELIABILITY
.9₃
.9₂
.9₁
12 drums
18 drums
36 drums
Std WANL data + "high" "I" and "C" reliability
12 drums
18 drums
36 drums
Std WANL data + "med" "I" and "C" reliability
12 drums
18 drums
36 drums
Std WANL data + "low" "I" and "C" reliability
12
18
36
1
10
10²
10³
10⁴
10⁵
ACTUATOR FAILURE RATE
FAILURES/MILLION

3.39

WANL CONTROL DRUM TRADE STUDY

RELIABILITY ASSUMPTIONS

	Assumption	Remarks
1.	Entire reliability comparison was based on reactor operational reliability with one drum in a failed state.	Unknown - Preliminary analysis indicates that this assumption results in a recommendation of 36 drums instead of 12 or 18 indicated by total systems approach.
2.	Assumed no reliability degradation due to the increased number or amplifiers required to control more than 18 actuators.	Favors more drums.
3	Reactor is considered in a failed state over 50% of the time a delta temperature of 380°R is reached.	Favors more drums.
4.	Credibility of a single drum failing in a full 180°R out condition was not considered.	Favors more drums.
5.	All failures occur at launch.	Favors more drums.
6.	Drum failure "out" and "in" are equally likely and no drums fail in place.	Favors more drums.
7.	Increased complexity, as number of drums increase, in reflector and dome has no effect on failure rate.	Favors more drums.
8.	All failure modes of drum, actuator, and SSCV result in random single drum failures.	Favors more drums.
9.	Assume a known core reliability degradation due to single drum failure.	Effect depends on direction of error.
10.	Only the cases of zero and one drum failure were considered.	Favors more drums.
11.	No mission abort groundrules were assumed.	Favors fewer drums.
12.	Single cycle 1 hr burn time assumed with no reliability degradation during coast periods.	Unknown

3.30

WANL CONTROL DRUM TRADE STUDY (cont.)

RELIABILITY ASSUMPTIONS

13.	Increased fabrication problems associated with 36 drum design has no effect on the unit failure rate.	Favors more drums.
14.	Only 12, 18, and 36 drum concepts considered.	Optimum may not be included.
15.	No in-flight repair capability or corrective measures considered.	Favors more drums.

MEMORANDUM

TO: A. D. Cornell

DATE: 5 September 1969
7850:M0268

FROM: E. J. West

SUBJECT: TPCV Actuator System Procurement Specification - Reliability Requirements

COPIES TO: J. J. Beereboom, W. M. Bryan, D. Buden, W. E. Campbell, V. M. Chang, J. W. Conant, D. W. Duncan, C. W. Funk, D. E. Glum, E. H. Hill, G. D. Johannsen, L. D. Johnson, G. S. Kaveney, J. M. Klacking, E. V. Krivanic, B. Mandell, I. L. Odgers, F. E. Porter, W. F. Pro, J. H. Ramsthaler, K. Sato, S. J. Williams, J. H. Yetto, R. F. Zwetter, G. Martin
NTO: W. H. Bushnell

REFERENCE: (a) Memo 7770:6150, dtd 11 Aug 69, A. D. Cornell to Distribution, same subject

The following specific changes are suggested to the referenced preliminary specification for TPCV actuator systems. Changes are underlined or bracketed.

3.1.2.1.3 Numerical Reliability

The reliability requirement of the actuator system shall be TBD. This requirement is based on successful completion of all prelaunch (final count-down only) and inflight checkout maneuvers and a one year space coast followed by 50 minutes of operation (covering the throttled to full rated thrust range). Operation to include a maximum of 10 cycles with a maximum of 30 days coast between cycles. AGC Reliability Specification ____________ defines the method of evaluating component ability to meet these requirements.

3.1.2.3 Useful Life

The actuator system shall be capable of completing a simulated useful life cycle in accordance with Table I where the cycle provides for the following events prior to and during a single mission of the NERVA vehicle:

A. Acceptance Test

B. Prelaunch Checkout

C. Boost

D. Coast (1 year)

3.32

3.1.2.3. Useful Life (cont.)

C. Engine Pre-Start Conditioning

D. Engine Start-up

E. Engine Steady-State Operation

F. Engine Throttling

G. Engine Shutdown

H. Coast (1 month)

I. Repeat C. to H. 10 cycles

3.3.1.1 Design Analysis

A. Stress Analysis per SNPO-C-1

B. Thermal Analysis

C. Reliability Analysis per AGC________

In general, the reliability analysis of all components will require the following:

1. Statistically designed acceptance testing in order to estimate the expected mean and variance of each measured response variable. In general, this requires an examination of the expected flight environments and their levels which will affect the response variables of interest. In addition, estimates are required of the precision and accuracy of the test instrumentation used in measuring the response variable, the extent of the interactions that can be expected among the imposed environments, and the expected repeatibility of the response variables.

2. Determine the functional relationship between measurable response variables. This requires an analysis of how shifts in one response variables effect the other response variables. A detailed failure mechanism may assist in this determination.

3.33

3. Define the boundaries of each response variable, outside of which, external compensation is required to prevent engine system failure.

4. Determine the probability of not exceeding the limits on each response variable. Combine the probabilities using a component math model which depects the response variable relationships.

5. Accept the design if the part is more reliable than the reliability requirements.

Redesign if the part does not meet the reliability requirement. (Redesign may not be required in the long run if the component results, combined by an engine made model, exceed the engine goal.)

6. Define a Qual. test program which will evaluate component ability to meet the useful life and maximum environmental exposure. These tests verify changes in probability of meeting the engine limits defined in Para. 3. as a function of time or cycles. Changes in reliability as a function of time or cycles would be indicated by shifts in means and/or variance. More than one mission duty cycle per component may be required in order to statistically define these shifts.

For response variables where continuous measurements during a test are available, estimates of the mean and variance may be derived from each simulated thrust cycle. For response variables with single data measurements per test, the results of several successive tests may be grouped to provide estimates of mean and variance.

The general reliability specification will outline this process but the specific details of analysis must be presented in each Acceptance Test and Qualification Test specification.

CLASSIFICATION CATEGORY
Unclassified
W. Porath 9/11/69
CLASSIFYING OFFICER DATE

E. J. West

E. J. West
Reliability
Reliability & Safety Analysis Section

3.34

MEMORANDUM

TO: J. H. Altseimer DATE: 18 September 1969
7850:M0276

FROM: J. H. Morison

SUBJECT: Reliability Input for Trade Study #17

DISTRIBUTION: J. H. Altseimer, W. M. Bryan, W. L. Davenport, F. Fairall, J. M. Klacking, A. V. Lundback, B. Mandell, I. L. Odgers, Section 7850 Personnel

ENCLOSURE: (1) PSS Trade Study Input

Enclosed is the reliability input requested by W. Davenport for Trade Study #17. The reliability of the final PSS design is estimated to be .9487. This figure is derived assuming the reliability of the I&C system was a constant for all systems considered and that internally generated contamination did not cause multiple failures. The failure rates were derived from Apollo and Gemini data. Enclosure (1) includes sections 3.6.1 through 3.6.4 of the trade study and an appendix with a description of the operation of the PSS, a PSS schematic, and the derivation and results of reliability estimates.

J. H. Morison

J. H. Morison
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
~~UNCLASSIFIED~~
W. M. Bryan [illegible]
CLASSIFYING OFFICER DATE

3.35

3.6 RELIABILITY

3.6.1 Objective

In order to meet the high reliability requirement of the NERVA program requirements document, as mentioned in Section 2.1, an iterative design and analysis procedure has been used in this trade study. Since a component design phase will follow the current effort, it was essential that the trade study result in choice of design alternatives which are capable of being developed to the necessary reliability as well as meeting the other system requirements. Simply stated; the objective of this effort has been to achieve a configuration as defined by (1) a piping and flow diagram (2) related designs,and (3) operating parameters that can achieve the required high reliability without requiring excessive performance or highly advanced state-of-the-art components.

The sections that follow discuss the reliability assessment of the selected alternatives, the reliability assessment and the reliability improvement potential.

3.6.2 Reliability Analysis

3.6.2.1

The reliability analysis and tradeoffs in this section represent a fourth phase of reliability considerations. The four phases may be described as follows:

3.6.2.2 Phase One

The first phase of reliability effort was the provision of reliability input during the initial design of the PSS system. This input generally consisted of intuitive comparisons of concepts with respect to reliability.

3.6.2.3 Phase Two

The second phase of reliability effort on the PSS development was the reliability analysis of the reference engine of July 1969 which was the result of the initial design effort. This analysis included the development of reliability models and the derivation of a predicted PSS reliability of $.9_{4}8$ for a 10 cycle mission. In doing this study component reliability values were derived from the current best estimate of man-rated hardware from Apollo and Gemi failure rate data, with no adjustment for the NERVA engine environment. These estimates, therefore, represent the current "state-of-the-art" of similar components.

3.6.2.4 Phase Three

Phase three of the reliability effort involved the analysis and tradeoff of changes in system configuration from that of the reference engine of July 1969. The changes were investigated in consideration of performance, flight safety, and reliability. Specific safety recommendations may be found in 3.7.2. Of major concern were the changes to the pneumatic gas tanks in order to comply with safety recommendations of capability of tank isolation, emergency recharge and emergency main propellant tank pressurization. Also filter bypass valves, actuator vent pressure release and separate PSOV shutoff systems were added. The other safety recommendations suggested were felt to not necessitate a basic change in configuration.

3.6.2.5 Phase Four, the Latest PSS

As a result of phase three analysis a new PSS configuration was designed and has been analyzed for reliability for a 10 cycle mission, a one year coast followed by 10 firings with 30 day coasts in between. Refer to Appendix 1 for a schematic of the system and the analysis of its operation and reliability. Again Apollo and Gemini data provided the source for the component reliability estimates. No adjustment was made for the difference between the NERVA environment and the Apollo and Gemini environments, the only exception being an updated probability of valve leakage of .000208 rather than the .000174 probability used previously and a reliability of $.9_6$ for the tank not leaking. The change in valve leakage reliability resulted from consideration of the increased leakage problems associated with the use of GH_2 and the tank probability of leakage was based on Aerojet's experience with pressure vessels and was required to analyze the potential of tank isolation during the long periods of deep space operation the NERVA will be subject to. It was found that using two shutoffs in series for each tank insured against tank leakage and redundant opening could still be provided by topping a tank through an adjacent tank using the vent valves. The reliability of this tank system was found to be $.9_7 6$. <u>This resulted in a reliability for this PSS system of $.9_4 87$ for a 10 cycle mission.</u> Changes other than the tank system configuration had little effect on the system reliability.

3.6.2.6 Tank Network Comparison

It was felt that due to the added complexity of the new tank network it would be advisable to compare the single shutoff tank network of the July PSS with the new isolated tank network of the latest PSS taking into account the instrumentation and joint leakage reliabilities. Taking these factors into account the reliability of the isolated tank network is $.9_5 6$ and the reliability of the old tank network with unisolated tanks is $.9_2 8489$. This indicates the tank network with isolated tanks is superior with respect to reliability, but it should be remembered that the reliability of the control system and no joint leakage may be much lower than is currently estimated. In this event a re-evaluation would be in order. Also past experience with tanks of the type to be used for the PSS indicates they have a very high reliability (i.e., usually R assumed to be 1.0), therefore, if tanks and joints can be made more reliable the unisolated tanks might prove to have acceptable reliability.

3.6.2.7 MPT Pressurization

The main propellant tank may also be considered a part of the PSS system. It's reliability was found to be essentially equal to 1.0 and therefore does not affect the overall system reliability a great deal.

3.6.3 Reliability Apportionment

The reliability estimate for the new PSS design ($.9_4 87$) is not greatly different from the estimate for the system of July 1969 ($.9_4 80$) and therefore given that the other subsystem reliabilities are about the same, the reliability apportionment for the PSS system will remain about $.9_6 5$.

3.6.4 Reliability Improvement Potential

The PSS system presented in this report is basically a reliable design and future improvements in reliability will probably have to come from improvement in component reliabilities.

APPENDIX 1

3.40

OPERATION OF THE PSS

The function of the PSS is to supply actuation gas to the various valve actuators of the NERVA engine and the gimbal actuators of the engine.

The system can be divided into three groups. These are:

1) The pressurized tank system including the shuttoff refill and vent valves associated with each of the five tanks.

2) The pressure regulation system.

3) The ten isolation valve systems for the valve actuator networks.

The main propellant tank pressurization system may also be included as part of the PSS system.

The layout of the groups mentioned above can be seen in Figure 1. The actuation gas comes from the tanks through the tank shutoffs or from the dome during engine steady state operation. The gas then passes through the pressure regulation system and on to each of the actuator shutoffs.

Each tank has two series isolation valves, a valve from the main propellant tank for emergency recharge and a valve to the vent manifold common to all five PSS tanks. There are five tanks with enough volume to give the system a "one out" capability for one shutdown,cooldown and restart to point of recharge. To minimize the probability of leakage two valves are in series on any one of the three leakage paths for each tank. Redundant tank opening is insured by allowing a tank to be used through an adjacent tank via the vent valves. The system also has an emergency recharge capability. If it is necessary to recharge for some reason (i.e., prolonged leakage) before the start of a burn, this can be done by venting the pneumatic tanks to space, filling them with LH_2 from the main propellant tank, and allowing solar radiation to heat the H_2 to a high pressure gas. The design must provide means of accomplishing this with electrical power only so solenoid valves are used. The shutoff valves for each group of actuators are actively redundant. The pressure regulation system employs standby redundancy.

The operation of the PSS is as follows:

At the beginning of childown the PSS tanks are still charged from a ground charge or the last engine burn. At the beginning of childown the PSS tank shutoffs open, the pressure regulation system begins to operate and all shutoffs open except those for the CDA's, DCV and CNDV, TNV systems. When start occurs after 62 seconds of childown the CDA and DCV shutoffs open and during full thrust all shutoffs but that for the CNDV, TNA are open. At the end of full thrust and thrust ramp down, 465 seconds after start of chill-down, the CDA and DCV shutoffs close. Both the TPCV shutoffs close about 20 seconds later during pump tailoff. At the end of pump tailoff, 600 seconds after start of childown, the PSOV shutoffs close and the CNDV, TNV shutoffs opens for pulse cooling and thrust nulling. At the end of pulse cooling/thrust nulling, 31,364 seconds after start of childown, all the PSS shutoffs close and coast begins.

Approximately 10 seconds after start begins the dome pressure is high enough such that the PSS tanks can be recharged. Recharge at the PSS continues as needed until about halfway through full thrust when the PSS tanks come fully charged and the tank shutoff closes. The PSS system is then driven by dome pressure until halfway through thrust ramp down when the tank shutoff opens. The PSS system then runs off tank pressure until the next run begins.

During coast all shutoffs of the PSS system are closed. The pressurization of the main propellant tank might also be considered a function of the PSS. The main tank is pressurized with exhaust from the valve actuators as shown in Figure 1. An alternate means of pressurizing the tank is the use of dome pressure or PSS tank pressure using the alternate recharge leg also shown in Figure 1.

Enclosure ([illegible])
7850:M0276

PSS RELIABILITY ESTIMATE

[illegible] TRADE STUDY

I. ASSUMPTIONS

The whole PSS system does not become contaminated.

1) Probability of a check valve failing to open is zero.

2) Reliability of a check valve not back leaking:

R_{ckl} = .999960 for one cycle.

3) Reliability of no tank leaks in one cycle:

$R_{tnk} = .9_6$

4) Reliability of signal sensing: $R_s = .9_450$ for one cycle.

5) Reliability of no leakage through a solenoid valve for one cycle: $R_c = .999792$

6) Reliability of no leakage through a pilot operated valve for one cycle: $R_c = .999858$.

7) Reliability of solenoid valve opening for one cycle:

$R_{vo} = .999935$

8) Reliability of pilot operated valve opening for one cycle:

$R_{pvo} = .999856$.

9) Reliability of pressure regulator: $R_{reg} = .999781$.

10) The mission in question is one year of coast in space followed by ten burns separated by thirty days coast.

II. SUMMARY OF PSS RELIABILITIES

	NEW SYSTEM WITH ISOLATED TANKS	OLD SYSTEM WITH UNISOLATED TANKS
Reliability of Tank System	$.9_76$	$.9_48985$
Reliability of pilot operated isolation valve systems	$(.9_58)^3$	$(.9_58)^3$
Reliability of solenoid isolation valve systems	$(.9_65)^7$	$(.9_55)^6$
Reliability of pressure regulation system	$.9_567$	$.9_567$

3.43

II. SUMMARY OF PSS RELIABILITIES (Cont'd)

	NEW SYSTEM WITH ISOLATED TANKS	OLD SYSTEM WITH UNISOLATED TANKS
Reliability of main propellant tank pressurization	$> .9_7$	$> .9_7$
Total system reliability excluding pressurization	$.9_4 87$	$.9_4 51$
Total System Reliability Including MPT Pressurization	$.9_4 87$	$.9_4 51$

The reliability of the old PSS system as estimated in July 1969 was $.9_4 80$. Different component reliability estimates resulted in the different estimate presented above for the system with unisolated tanks.

In order to compare the new and the old tank networks it was assumed that the reliabilities of sensing failure and sending signals to valves were $R_s = .9_4 50$.

The probability of any leak not being catastrophic was:

$R_{s1} = .75$

The probability of a joint to a component not leaking was:

$R_j = .999925$.

Making these assumptions:

The old tank network has a reliability of - $.9_2 8489$

The new tank network has a reliability of - $.9_5 6$

3.44

Photostatic (1)
7856:M0276

1. [illegible]

A. [illegible] Five Isolated [illegible]

The reliability of a single tank for 10 cycles (R_{ot}) is the reliability of it having a sufficient pressure charge at the beginning of each start (R_p) and the reliability of being able to use that charge for each burn, R_{up}. Therefore:

$$R_{ot} = R_p \cdot R_{up}$$

The reliability of having four out of five tanks work for 10 cycles is then:

$$R_t = R_{ot}^4 + 5\ (1-R_{ot})\ R_{ot}^3$$

a) R_p is the reliability of a tank not developing a leak during any of the ten cycles or if it does develop a leak is rechargeable. Therefore:

$$R_p = [(R_{nl}\ \text{one year}) + (1-R_{nl}\ \text{one year})\ R_{rc}]$$

$$[R_{nl}^9 +$$

$$R_{nl}^8\ (1-R_{nl})\ R_{rc}$$

$$R_{nl}^7\ (1-R_{nl})\ R_{rc}^2$$

$$R_{nl}^6\ (1-R_{nl})\ R_{rc}^3$$

$$R_{nl}^5\ (1-R_{nl})\ R_{rc}^4$$

$$R_{nl}^4\ (1-R_{nl})\ R_{rc}^5 +$$

$$R_{nl}^3\ (1-R_{nl})\ R_{rc}^6 +$$

$$R_{nl}^2\ (1-R_{nl})\ R_{rc}^7 +$$

$$R_{nl}\ (1-R_{nl})\ R_{rc}^8 +$$

$$(1-R_{nl})\ R_{rc}^9\ ]$$

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Where R_{nl} is the probability of a tank not leaking during the cycle and R_{c} is the probability of being able to [illegible] from the [illegible] during the three cycles.

R_{t1} [illegible]

$R_{t1} =$

$$(R_{inl})(R_{ck1} R_c + (1-R_{ck1})R_c + (1-R_c)R_{ck1})(R_c^{2}+2(1-R_c)R_c) \times$$

$$(R_{nl}^{2}+2(1-R_{nl})R_{nl})$$

R_{vo} for a single tank [illegible] all [illegible] of [illegible]

$$R_{tc} = (R_{vo}^{3}) + (1-R_{vo})\, R_{vo}^{2} + \left[(1-R_{vo})\,(1-R_{vo}^{2})\,(R_{vo})^{2} + (1-R_{vo})\,(1-R_{vo}^{2})^{2}\,(R_{vo})^{2} \right] \approx 0$$

b) R_{tp} is the probability of being able to use the pressure in a tank.

$$R_{tp} = (R_{pvo}^{2})^{2} + (1-R_{pvo}^{2})^{2})(R_{pvo}^{2})^{2}\,(R_{vo}^{2})^{2} + \left[(1-(R_{pvo})^{2})^{2}\,(R_{pvo})^{2}\,(R_{vo})^{2} + (1-(R_{pvo})^{2})^{3}\,(R_{pvo})^{2}(R_{vo})^{2} \right] \approx 0$$

B. Reliability of Pressure Regulation, Shutoff Operation and [illegible] System Reliability

In addition to the reliability, R_t, of obtaining actuation gas from the pressure tanks the reliability of the PSS system is dependent upon the reliability of regulating the gas pressure and supplying it to the various actuators through each of ten shutoff systems. The pressure regulation system employs standby redundant regulation and pilot operated pilot valves are used to control the flow through them. There are seven active redundant solenoid valve shutoffs and three pilot operated pilot valve shutoffs. The pressure regulation system and shutoffs we shall assume must all work, therefore.

[illegible]

[illegible]

c. Reliability of [illegible] Tank Pressurization System

The main propellant tank will generally be recharged with [illegible] from the actuator but standby recharge can be achieved through [illegible] one of the PGS tanks. The tank will be pressurized with [illegible] provided the relief valve reseats and the parallel redundant pilot operated shutoff valves open. The standby pressurization will work provided a pilot operated shutoff opens and a pressure regulator works. Assuming the reliability of the sources is one, the probability, R_{tp}, of successful [illegible] pressurization for ten cycles is:

$$R_{tp} = R_{rl}[(R_{pvo}^{10})^2+2(1-R_{pvo}^{16})R_{pvo}^{16}] + \{1-R_{rl}[(R_{pvo}^{10})^2+2(1-R_{pvo}^{10})R_{pvo}]\}R_{reg}\ldots$$

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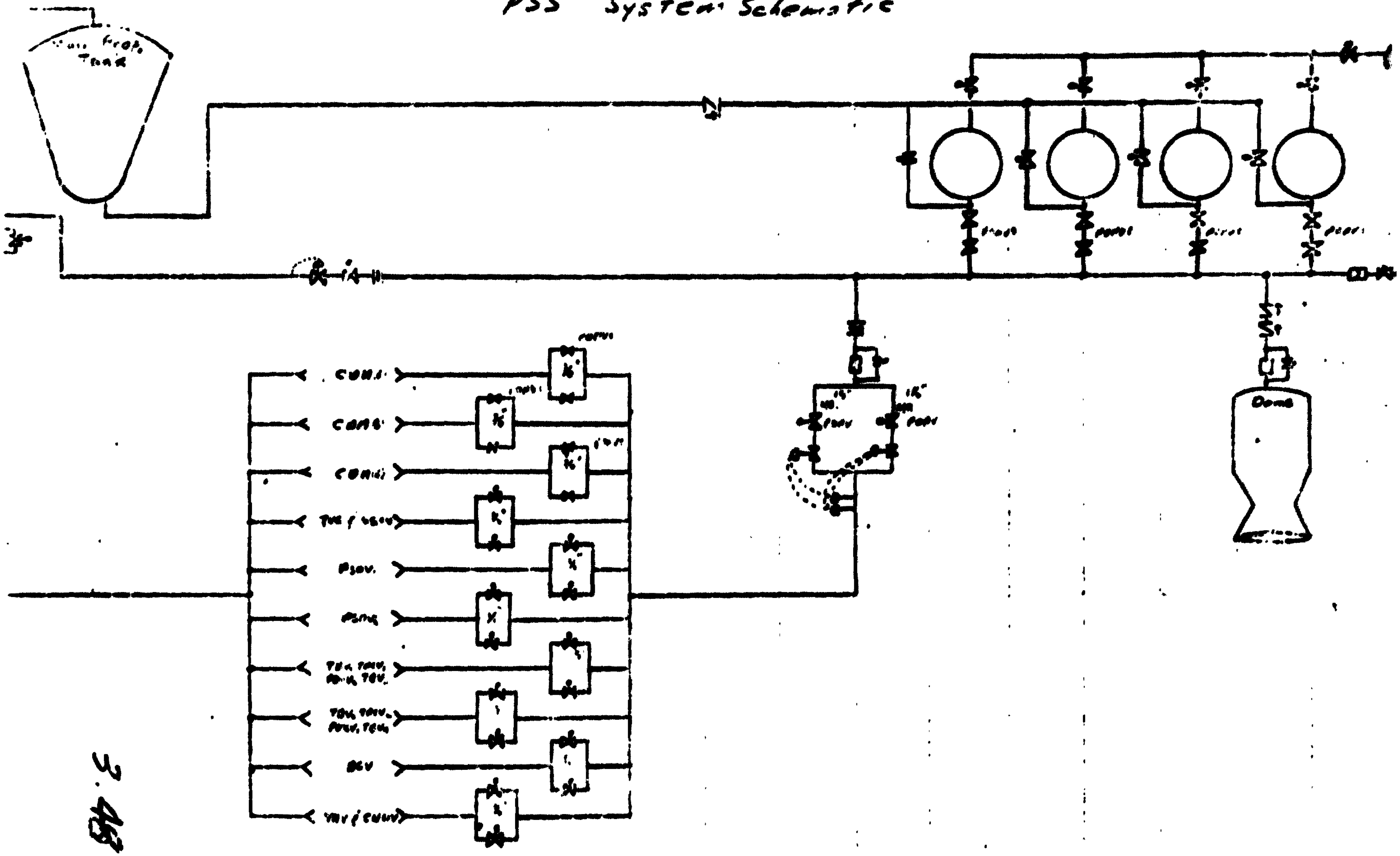
Figure 1
PSS System Schematic



MEMORANDUM

TO:	D. F. Vanica	DATE:	10 October 1969 7850:M0283
FROM:	C. T. Lang		
SUBJECT:	Reliability Input to Trade Study No. 016 (Emergency Mission)		
COPIES TO:	7850 Personnel		
ENCLOSURES:	(1) Failure Modes Analysis Summary (2) Failure Mode Effects and Criticality Analysis (3) Failure Mode Matrix (4) Critical Failure Explanations		

The emergency mission has tentatively been defined as a reduced thrust level mode of operation. This eliminates the need for decisions under emergency conditions.

Cooling of the core will also be required until the nuclear hazard has been elminated by attainment of a sufficiently long lifetime orbit.

The primary objective of this analysis is to determine the most reliable emergency mission operating point for the non-nuclear subsystems of the NERVA engine. In addition to the normal full thrust mode, four possible emergency thrust levels are compared to determine if any one level is significantly more reliable than another. These levels are tabulated below:

Thrust (lb)	Isp (sec)	T_c (°R)	P_c (psia)
75,000	825	4600	450
40,000	575	2425	245
38,000	560	2300	232
34,000	530	2070	209
30,000	500	1850	185

A cursory analysis indicates that since operating temperatures throughout the engine system generally decrease with the lower thrust levels, the thermal stress also decreases, resulting in increased reliability.

The maximum length of time anticipated for emergency mode operation is 1000 seconds. To provide a minimum total impulse (30,000 lbs x 1000 sec = 3×10^7 lb-sec) for the emergency mission, the following burn times are required:

Thrust, F (lbs)	Time, t (sec)
40,000	750
38,000	790
34,000	882
30,000	1000

From this consideration, the shorter length of burn time would tend to increase reliability. However, the engine is required to operate at full thrust for 3600 seconds. The difference between 750 and 1000 seconds is probably insignificant.

To assist in the selection of the most reliable emergency mode, a system failure mode analysis was conducted. This analysis examines each component failure effect on the engine capability to complete an emergency mission. With a given component failure mode, a determination is made relative to the level of thrust and component redundancies that can be maintained. A total of 95 modes of failure were analyzed. Enclosure (1) categorizes these modes.

Approximately half of the failure modes (43) permit continued full thrust. 75% of these (32 of 43) permit dual pump operation. This would seem to indicate that automatic reduction to low thrust or single pump operation would be an unduly restrictive definition for the emergency mission mode.

Some component failures prevent normal cooldown through the auxiliary cooldown circuit. In this event the emergency cooldown may be accomplished by flowing LH_2 through the PSOVs.

Enclosure (2) contains the failure modes analysis performed on the reference engine components.

Enclosure (3) is a matrix of the failure modes analysis showing the failure modes by components, if they effect normal cooldown and the mode of operation after the failure.

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Enclosure (4) discusses those failures which result in the following:

a. Complete loss of thrust.

b. Single pump reduced thrust only.

c. Single pump, full thrust.

All of these modes of failure have either redundancy provided or a low probability of failure exists as evidenced by previous experience.

Conclusion:

Any one level of the four emergency thrust levels is not significantly more reliable than another.

The emergency mission mode should consider the failure mode that has occurred and the resulting engine capability. The desirable thrust level in order to prevent propagation of the failure should be considered.

C. T. Lang
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

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Enclosure (1)
7850:M0283

FAILURE MODES ANALYSIS SUMMARY

Total No. of Failure Modes Considered	95
No. of failure modes which prevent normal cooldown	11
No. of failure modes which prevent maintaining full thrust or emergency mission minimum thrust	5
No. of failure modes which prevent full thrust but emergency mission thrust levels are possible	46
Permits Dual Pump	43
Permits Single Pump Only	3
No. of failure modes which permit full thrust	44
Permits Dual Pump	32
Permits Single Pump Only	12

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Enclosure (2) 7850:LM0283 SHEET 10

DATE 6 October 1969

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang DEPT. 7850 EXT. ____

APPROVED BY E. J. Neal

Mode Ident. No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: PBOV					
	Premature Closure Failure to Open		No Change	Full thrust obtained with one pump leg.	One pump leg full or reduced thrust.	
	External Leakage		No Change	Shortened mission due to LH_2 loss. Undesired thrusting.	Full thrust, one or both pumps.	
	Internal Leakage		None	None - Redundant sealing by actuation of DKVA.	Full thrust, one or both pumps.	
	Component: Pump Inlet Lines (PIL)					
	External Leakage		None	Momentary drop in thrust until compensation occurs.	Minor leakage - Both pumps at full thrust. Some I_{sp} loss. Major leakage - One leg full or reduced thrust.	
	Component: Main Pumps					
	Failure to Increase Pressure			Momentary drop in thrust until compensation occurs with surviving pump.	Minor efficiency loss - Both pumps at full thrust. Major loss - One pump full or reduced thrust.	
	Component: Pump Discharge Line					
	External Leakage Upstream of DKVA		Lower stress level.	Momentary drop in thrust until compensation or isolation occurs	Full thrust with both pumps if minor leakage. Full thrust with one pump if major leak.	
	External Leakage Downstream of DKVA		Lower stress level	Momentary drop if compensation is possible or permanent drop in thrust and I_{sp} if major leakage.	Full thrust with both pumps if minor leakage. Reduced thrust with one or both pumps.	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang DEPT. 7850 EXT. ____

APPROVED BY E. J. West

Mode Ident. No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: DKVA					
	Reverse Leakage When Pump Leg is Down (Fail to close considered negligible)		Lower stress level given a failed leg or operation on one leg.	Loss of thrust and I_{sp} due to flow through tank relief. Possible overpressurization of Main Propellant Tank. (Assuming PSOV cannot withstand reverse pressure) Some loss of flow for thrust and I_{sp}.	Single pump with minor loss in I_{sp} and thrust.	
	Reverse Leakage During Cooldown		Lower stress level	No full thrust effect.		
	Fail to Open		None	One pump operation.		
	Premature Close			Pump stall, overspeed kill by TBV_1.		
	Component: Nozzle Skirt					
	External Coolant Leak		Lower stress level	Loss in I_{sp}	Reduced thrust with one or both pumps to lessen severity of leakage. Low T_c desired.	
	External Hot Gas Leak			Loss in thrust. Side thrust loads.		
	Internal Coolant Leak			Loss in thrust.		
	Component: Nozzle					
	External Coolant Leak		Lower stress level	Loss in I_{sp}	Reduced thrust with one or both pumps to lessen severity of leakage low T_c desired.	
	External Hot Gas Leak			Loss in thrust. Side thrust loads.		
	Internal Coolant Leak			Loss in thrust.		

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang DEPT 7850 EXT
APPROVED BY E. J. West

Mode Ident No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: **Bolt Coolant Line**					
	External Leakage		Lower stress level	Loss in I_{sp} or loss in thrust if bolt damage occurs.	Reduced thrust with one or both pumps to lessen severity of leakage. Low T_c desired.	
	Component: **Pressure Vessel and Closure**					
	External Coolant Leakage		Lower stress level	Loss in I_{sp}	Reduced thrust with one or both pumps.	
	Coolant Leak to Hot Gas			Loss in thrust		
	Component: **Hot Gas Bleed Port**					
	Improper Turbine Drive Gas Temperature		Lower stress level	Reduced thrust required to lower gas temperature.	Reduced thrust with one or both pumps.	
	Improper Turbine Drive Gas Weight Flow			Momentary loss of thrust until compensating TPCV control.	Lower thrust with one or both pumps.	
	Improper Mixing Results in Duct/ Elbow Burn Thru			Reduced thrust required.	Lower thrust with one or both pumps. Low T_c desired.	
	Component: **Diluent Line**					
	External Leakage (Excessive turbine drive gas temperature)		Lower stress level	Reduced thrust required	Reduced thrust with one or both pumps. Low T_c desired	

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Enclosure (1)
7850 M0263

SHEET (w)

DATE 6 October 1962

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang DEPT 7850 EXT ____

APPROVED BY E. J. West

Mode Ident No	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component <u>DCV</u>					
	Permits Excessive Flow		Effectiveness of control at low pressure	Loss in turbine efficiency. Momentary drop in thrust until TPCV increase hot gas flow.	Slight loss in I_{sp}. Full thrust with both pumps permits max efficient use of excess diluent unless full TPCV fails to maintain full thrust. Then reduced thrust with one or both pumps.	
	Prevents Adequate Flow			Reduced thrust required due to excessive turbine drive gas temperature.	Reduced thrust one or both pumps.	
	Component: <u>Turbine</u>					
	Fails to Convert Heat Energy to Kinetic Energy (Binding, distortion, damage)		Lower thermal and pressure stress levels.	Momentary loss in thrust until surviving turbine speed is increased	Full thrust with both or one pump.	
	External Gas Leakage		Critical speeds	Momentary loss until isolation of failure and increase in surviving turbine speed.	Full thrust with one pump.	
	Component: <u>TPCV</u>					
	Fails to Open		Effectiveness of control at low pressure may dictate operating with one TPCV even if two are good.	Full thrust with surviving TPCV control.	Full thrust both pumps	
	Permits Excessive Gas Flow			Momentary increase in thrust until surviving TPCV compensates and/or TBV isolates bad TPCV.		
	Prevents Adequate Gas Flow			Momentary loss in thrust until surviving TPCV compensates. TBV may not isolate until lower thrust levels are desired.		

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang DEPT 7850 EXT ____

APPROVED BY E. J. West

Mode Ident. No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: TBV (Upstream of TPCV					
	Premature Closure			Momentary loss in thrust until surviving TPCV opens to compensate.	Full thrust both pumps.	
	Fails to Isolate TPCV which is: Permitting Excessive Gas Flow			Increased thrust until surviving TPCV can reduce flow. Reactor power shutdown required.	Reduced thrust.	
	Preventing Adequate Gas Flow			Momentary loss in thrust until surviving TPCV increases flow Reactor power shutdown required.		
	Component: TBV (Downstream of Crossover Duct					
	Premature Closure Fails to Isolate TPA Leg with: PSOV Failed Closed		Lower stress levels (Easier to Close)	Momentary loss in thrust until surviving TPCV regains control. Destructive failure of engine due to overspeed of unloaded turbine.	Reduced thrust with one pump	
	Pump Inlet Line Leakage			Loss in I_{sp} due to leak unless PSOV closes to isolate, then destructive failure as above	Full or reduced thrust with both pumps or reduced thrust using pump leg with leakage	
	Inefficient Pump (Binding, Leakage or Damage)			Momentary loss in thrust until compensation with surviving TPA unless damage is potentially hazardous, then engine slowdown or shutdown is required.	Reduced thrust with both pumps to lessen probability of destructive damage Impending failure may be difficult to predict.	

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FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE 6 October 1962

PREPARED BY C. T. Lang DEPT 7850 EXT ____

APPROVED BY E. J. West

Mode Ident. No	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: Turbine Inlet Line (Upstream of Turbine TBV)					
	External Hot Gas Leakage		Lower stress levels	Reduced thrust required (Compensation with TPCV increases temperature). Excessive leakage results in reduced thrust.	Reduced thrust with both or one pump.	
	Component: Turbine Inlet Line (Between TBV and Turbine Inlet)					
	External Hot Gas Leakage		Lower stress levels	Momentary drop in thrust until isolation by PSOV - TBV closure and TPCV increasing load on surviving turbine.	Full thrust with one pump (Failure may be difficult to detect).	
	Component: Turbine Exhaust Line					
	External Hot Gas Leakage		Lower stress levels	Minor loss in thrust and I_{sp} from skirt nozzles. Undirected thrust if loss in coolant causes skirt burn thru	Reduced thrust with both or one pump (lower T_c desirable).	
	Component: Skirt Extension					
	External Coolant Gas Leakage		Lower stress levels	Minor loss in thrust and I_{sp}.	Reduced thrust with both or one pump.	
	External Hot Gas Leakage			Reduced temperature required potentially destructive propagating failure.		
	Internal Coolant Leakage			Minor unbalanced thrust due to flow interruption.		

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FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. I. Lang DEPT 7850 EXT ____

APPROVED BY E. West

Mode Ident No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: Diversion Valve Inlet Line					
	External Leakage		Lower stress levels	Loss in I_{sp} and thrust due to loss in flow thru core.	Reduced thrust with one or both pumps to prevent propagation.	
	Component: CNDV					
	Premature Closure Leakage to Auxiliary Turbine		Lower stress levels	Potential damage due to AT spin up or damage. No effect - flow is routed back to core thru TNVs. Possible AT damage	Full thrust with one or both pumps.	
	Fail to Close (Normally open to core) a. Both Valves b. At Least One Valve			Longer cooldown due to lack of auxiliary compressor fed coolant or reduced pressure if only one valve diverts. May require restarting engine.	Full thrust both pumps.	
	Component: TNV					
	External Leakage to Hull		Lower stress levels (during thrusting).	Loss of I_{sp} and thrust.	Reduced thrust with one or both pumps to reduce propagation probability. Emergency mission not possible	
	Premature Open or Stuck in Open Position.			Complete loss of thrust.		
	Fail to Close. (Normally open to ATKV and ACV)		No effect - low thrust ullage cooldown pressure will be the same as full thrust cooldown pressures.	Nulling of coolant flow thrust.	Full thrust with one or both pumps. Failure to null does not effect thrusting capability	
	a. Both Valves			a. Complete loss.		
	b. At least one valve			b. Partial loss.		

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FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. I. Long DEPT 7850 EXT ____
APPROVED BY F. J. West

Mode Ident No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: Propellant Return Line					
	External Leakage		Lower stress levels	Loss of I_{sp} and thrust due to loss of flow thru core	Reduced thrust with one or both pumps to decrease propagation probability.	
	Component SSCV					
	Inadequate Flow to Stem Coolant		Effectiveness of reactivity control at low pressure	Reduced thrust required to lower stem temperature	Reduced thrust with one or both pumps (Lower reactor temp. desired).	
	Excessive Stem Coolant Flow			Reduce thrust desired to nullify loss of SSCV control. Excess reactivity requires drum control if available.	Full thrust with one or both pumps permits maximum efficient use of excess stem coolant.	
	Component SSCV Bypass Line					
	External Leakage		Lower stress levels	Loss in I_{sp} and thrust.	Reduced thrust with one or both pumps to reduce propagation probability.	
	Component: SSCV Stem Coolant Line (SCL)					
	External Leakage		Lower stress levels	Reduced thrust required to lower stem temperature. Minor loss of I_{sp} and thrust. (Reduced stem flow during cooldown)	Reduced thrust with one or both pumps to reduce propagation probability.	

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Enclosure (2) SHEET (4
7850 M02A)
DATE 6 October 1969

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang DEPT 7850 EXT ____

APPROVED BY E. J. West

Mode Ident. No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: TNKV					
	Reverse Leakage - (Excess flow to stem bypassing SSCV control)			Momentary increase in reactivity and temperature until SSCV compensates or reaches max. bypass then drum control is required. No full thrust effect.	Reduce thrust with one or both pumps. (Low P_c required to reduce reactor moderation).	
	Fail to Open			Restart required to provide coolant. Loss in I_{sp}.	Full thrust both pumps.	
	Component: ACKV					
	Reverse Leakage - (Possible damage to auxiliary compressor or UCSV)		Lower stress levels	May overpressurive main tanks if UCSV leaks in reverse. Damage to AC effects cooldown capability only if high pressure lines.	Reduced thrust with one or both pumps to reduce possible AC damage. (This failure may be impossible to detect until cooldown is attempted).	
	Fail to Open			No thrust effect. Restart required to provide coolant.	Full thrust both pumps.	
	Component: ATKV					
	Fail to Open Reverse Leakage (Possible damage to auxiliary turbine)		Lower stress levels	Restart required to provide coolant. No full thrust effect - leakage is stopped by ACV and CNDV.	Full thrust. Reduced thrust with one or both pumps to lessen damage to AT. (This failure may be impossible to detect until cooldown is attempted).	
	Component: ACV					
	Reverse Leakage (Possible damage to AT)		Lower stress levels	No full thrust effect. Leakge is stopped by CNDVs and routed thru ATKV to core.	Full thrust. Reduced thrust with one or both pumps to lessen damage to AT. (This failure may be impossible to detect until cooldown is attempted).	

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FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE 6 October 1969

PREPARED BY C. T. Lang DEPT 7850 EXT

APPROVED BY E. J. West

Mode Ident No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: ACV (cont.)					
	Permits Excessive Flow to AT			No full thrust effect. Shorter cooldown pulses will result.	Full thrust.	
	Prevents Adequate Flow to AT			No full thrust effect. Longer cooldown pulses will result. Less efficient cooling.	Full thrust.	
	Fail to Close (Normally closed to AT but control valves tend to fail in place. Possible damage at AT)			No full thrust effect.	Full thrust	
	Premature Opening (Possible AT damage)			No full thrust effect	Full thrust.	
	Component: UCSV					
	Premature Open			Coast-depletion of propellant. No full thrust effect.	Full thrust one or both pumps. (Main TPA flow will stop UCSV flow)	
	Fail to Open		None. No change in cooldown operation.	No full thrust effect. Normal cooldown obviated. Pulse cooling thru main PSOVs required or continue thrusting in emergency mode.	Full thrust one or both pumps.	
	Component: Coolant Inlet Line (CIL)					
	External Leakage		None	No full thrust effect. Cooldown efficiency and I_{sp} loss.	Full thrust one or both pumps.	

3.6.2.1

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang DEPT 7850 EXT
APPROVED BY E. J. West

Mode Ident No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: SSKV					
	Fail to Open Reverse Leakage		None	(Complete loss of stem coolant) No full thrust effect. Cooldown bypassing stems	No thrust. Full thrust one or both pumps.	
	Component: Auxiliary Turbine Inlet Line (ATIL)					
	External Leakage		None	No full thrust effect. Cooldown: Some loss compensated for by ACV. Major leakage requires cooldown by PSOVs or return to thrust mode.	Full thrust	
	Component Auxiliary Turbine Bypass Line ATBL					
	External Leakage		None	Loss of I_{sp} due to loss of flow to core.	Reduced thrust to prevent propagation probability.	
	Component: ACV Inlet Line					
	External Leakage		None	No full thrust effect. Cooldown - Loss in AT pressure.	Full thrust.	
	Component: Thrust Nulling Line (TNL) Nozzles					
	External Leakage		None	No full thrust effect. Nulling undirected thrust vector.	Full thrust.	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang DEPT 7850 EXT
APPROVED BY E. J. West

Mode Ident No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component PSS					
	Failure to Provide Adequate Specific Gas Flow Rate and Pressure to Actuations		Lower stress level between dome and regulator circuit	Engine cannot operate	No emergency mission possible.	
	Failure to Provide Adequate Total Gas Flow		None - Minimum dome pressure (250 psia) will be sufficient for continuous running of all actuators. Estimated dome temperature (110°R) not expected to have adverse effect.	Shorter mission duration.	Shorter duration can run at full thrust with one or two pumps. Single pump could be utilized to conserve gas.	
	Component: Storage Tanks					
	xternal Leakage			Abort to emergency mission or continue at thrust levels adequate to provide actuation gas from dome. Loss of pressure from dome can be isolated by closure of tank shut-off valves.	Can operate at full thrust with one or both pumps	
	Component: Tank Shut-off Valves (TSOV)					
	Failure to Open			Fails to start or uncontrolled. Shutdown (Redundant valves reduce probability of this failure).	No possible mission if no start. If uncontrolled shutdown, catastrophic failure.	

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FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE 6 October 1969

PREPARED BY C. T. Lang DEPT 7850 EXT

APPROVED BY E. J. West

Mode Ident No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component <u>Dome Check Valves</u>					
	Internal Leakage				Full thrust, both pumps.	
	Reverse Leakage (Loss of tank pressure through dome)			Failure to shutdown or cool-down. Series redundancy reduces probability of failure (restart to run off of dome).		
	Fail to Open			(Tanks not repressurized).	Reduced thrust - one pump to conserve tank pressure.	
	Component: <u>Regulator</u>					
	Permits Excessive Pressure			None - Momentary surge or drop in pressure until redundant standby regulator controls pressure.		
	Prevents Adequate Pressure			If ground rule is abort when loss of redundancy, then go into emergency mission with full thrust capability.		
	Component: <u>Pressure Switch</u>					
	Failure to Detect High or Low Pressure			None - Parallel redundancy on switch	Full thrust capability.	
	Component: <u>PSS Circuit Isolation Valves</u>					
	Failure to Open			None - Parallel redundancy on valves.		

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FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

PREPARED BY C. T. Lang C 7850 EXT
APPROVED BY E. J. West

Mode Ident. No.	Failure Mode	Criticality Category	Component Effect in Low Thrust Operation	Subsystem Effect	Emergency Mission Engine Effect	Means of Detection
	Component: **Filters**					
	Clogging			Insufficient gas flow possible insufficient NPSH and pump cavitation.	Low thrust - both pumps	
	Component. **Stage Pressurisation Check Valves**					
	Fail to Open			Loss of ullage gas during periods of non-thrusting		
	Reverse Leakage					

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Enclosure (3)
7850:M0283

FAILURE MODE MATRIX

Component	Failure Modes: Fail to Open	Fail to Close	Premature Open	Premature Closure	Leak Ext.	Leak Int.	Leak Rev.	Inad. Flow/Press Temp.	Excess Flow/Press Temp.	Prevents Normal Cooldown	No Thrust	Dual Pump: Full Thrust	Dual Pump: Low Thrust	Single Pump: Full Thrust	Single Pump: Low Thrust
PSOV	X									No				X	
					X					No		X (desired)			
						X				No		X			
PIL					X					No				X	
TPA								X		No				X	
PDI-1					X					No				X	
-2					X					No			X		
DKVA	X									No				X	
		X (redundancy provided)					X			No				X	
				X						No				X	
Nozzle Skirt					X (coolant)					No			X		
					X (hot gas)					No			X		
						X (coolant)				No			X		
Nozzle					X					No			X		
					X					No			X		
						X				No			X		
Bolt Coolant Line					X					No			X		
[illegible]V and Closure					X					No			X		
						X				No			X		
ATBL					X					No			X		
ACV Inlet Line					X					No		X			
TNL and Nozzles					X					No		X			
PSS Tanks					X					No		X			

3.67

Enclosure (3)
7850:M0283

FAILURE MODE MATRIX

Component	Failure Modes: Fail to Open	Fail to Close	Premature Open	Premature Closure	Leak Ext.	Leak Int.	Leak Rev.	Inad. Flow/Press Temp.	Excess Flow/Press Temp.	Prevents Normal Cooldown	No Thrust	Dual Pump: Full Thrust	Dual Pump: Low Thrust	Single Pump: Full Thrust	Single Pump: Low Thrust
SSCV-BPL					X					No			X		
SSCV-SCL					X					No			X		
TNKV							X			No			X		
	X									No		X			
ACKV							X			No			X		
	X									Yes		X			
ATKV	X									Yes		X			
						X				No			X		
ACV							X			No			X		
								X		No		X			
									X	No		X			
		X								No		X			
			X							No		X			
UCSV			X							No		X			
	X									Yes		X			
CIL					X					Yes		X			
SSKV	X									No	X				
							X			No		X			
ATIL					X					No		X			

3.68

Enclosure (3)
7850:M0283

FAILURE MODE MATRIX

Component	Failure Modes: Fail to Open	Fail to Close	Premature Open	Premature Closure	Leak Ext.	Leak Int.	Leak Rev.	Inad. Flow/Press Temp.	Excess Flow/Press Temp.	Prevents Normal Cooldown	No Thrust	Dual Pump: Full Thrust	Dual Pump: Low Thrust	Single Pump: Full Thrust	Single Pump: Low Thrust
TSOV's	X									No	X				
						X				No		X			
DKV	2X									No					X
							X			No		X			
Regulators									X	No		X			
								X		No		X			
Pressure Sw.		X								No		X			
PSS Isolation Valves Turbine Control	2X									No				2X	
PSOV Control	X									Yes	X				
SSCV and TVA	X									No	X				
CDA	3X									No			3X		
UCSV	X									Yes		X			
Filters								2X		No			2X		
Stage Pressurization	2X						2X			No			2X		
													2X		
Hot Gas Bleed Port									X	No			X		
								X		No			X		
										(No / X (mixing))			X		
Diluent Line					X					No			X (low r_c)		
DCV									X	No			X		
								X		No			X		

3.64

FAILURE MODE MATRIX

Component	Failure Modes: Fail to Open	Fail to Close	Premature Open	Premature Closure	Leak Ext.	Leak Int.	Leak Rev.	Inad. Flow/Press Temp.	Excess Flow/Press Temp.	Prevents Normal Cooldown	No Thrust	Dual Pump: Full Thrust	Dual Pump: Low Thrust	Single Pump: Full Thrust	Single Pump: Low Thrust
Turbine								X		No		X			
					X					No				X	
TPCV	X									No		X			
									X	No		X			
								X		No		X			
TBV-1				X						No		X			
		X								No			X		
TBV-2				X						No				X	
		X								No					X
Til-1					X					No			X		
Til-2					X					No				X	
Skirt Ext.					X (cooling)					No			X		
					X (hot gas)					No			X		
						X				No			X		
DVIL					X					No			X		
CNDV				X						Yes			X		
		X								No		X			
						X				No		X			
TNV			X							Yes	X				
		X								Yes		X			
					X					Yes			X		
PRL					X					Yes			X		
SSCV								X		No			X		
									X	No		X			

3.7C

CRITICAL FAIL ?E EXPLANATIONS

Failures Resulting in Complete Loss of Thrust

1. Thrust nulling valves prematurely open - electronics must be fail safe.

2. SSKV fails to open - low probability of failu_, no redundancy.

3. Pneumatic system tank shut-off valves fail to open - parallel redundant paths provided.

4. Pneumatic system PSOV isolation valves fail to open - parallel redundancy provided.

5. Pneumatic system SSCV isolation valves fail to open - parallel redundant paths provided.

Failures Permitting Single Pump Reduced Thrust Only

1. TBV-2 fails to close - second order failure. Failure to isolate a failed pump leg.

2. Pneumatic system dome check valves fail to open (2 each) - low probability of failure.

Failures Permitting Single Pump at Full Thrust

1 thru 11. Eleven failures associated with pump feed components for which parallel leg redundancy is provided.

12. Turbine inlet line leakage which can be isolated and a parallel path is provided.

MEMORANDUM

TO: L. A. Shurley

DATE: 2 October 1969
7850:M0291

FROM: R. D. Zonge

SUBJECT: Reliability Input to Skirt Extension Trade Study

COPIES TO: J. J. Beereboom, H. J. Bronner, W. M. Bryan, D. Buden, J. W. Conant, D. S. Duncan, C. W. Funk, G. S. Kaveney, J. L. Klacking, I. L. Odgers, B. Mandell, E. A. Sheridan, E. M. Takemori, E. J. West, 7850 Personnel
NTO: W. H. Bushnell

ENCLOSURE: (1) Preliminary Reliability Comparison of Gas Cooled, Cryogenically Cooled, and AG Carb Skirt Extension Concepts

A preliminary reliability comparison of the present gas cooled, cryogenically cooled, and AG Carb skirt extension concepts has been completed and is transmitted herewith as the Reliability input to the skirt extension trade study. A condensed version of the comparison was given to Design Engineering for DEI presentation.

The comparison is based on FMAs of the gas cooled (P/N 1136173), cryogenically cooled (P/N 1136165 aluminum tube bundle), and AG Carb (Drawing #1136077 plus an external stiffening structure such as Intremold added), extensions. In addition, it was necessary to assume that all necessary fabrication development had been completed and an acceptable fabrication process had been adopted for each concept. If such an assumption had not been made, neither AG Carb nor the cryogenically cooled concepts could have been considered in their present form (Drawing No's 1136077, and 1136165, respectively).

The AG Carb extension needs a stiffening structure, such as Intremold, to prevent failure during firing from vibration or "flutter". There is also a high probability of fabrication anomalies in the critical flange area. Changes in fabric ply orientation during cure which are almost certain to occur, based on experience with large high-silica tape wrapped parts for the 100 and 260 inch solid rockets, could change the controlling failure mode from tension parallel to the plies to interlaminar shear, peel, or tension perpendicular to the plies. Material tensile strength parallel to the plies is roughly ten times its strength in the other directions. In the case of the large solids mentioned above, the tape wrapped structures were enclosed in metal (solid or honeycomb) cans which were the actual load carrying structures. Consequently, considerable development work will be necessary to demonstrate if and how an acceptable component can be fabricated. Although AGC experience has been primarily with tape wrapped components, the "shingle lap" and "rosette" lay-up methods offer some advantages and should also be considered.

Also, fabrication experience with the aluminum tube bundle (cryogenically cooled) concept has been very meager. The Able-O combustion chamber was an aluminum tube bundle, but the tubes were relatively heavy walled, and the structure was all welded. Welding, as a method of joining the proposed thin-walled tubes is considered impractical because of the extremely high probability of undercutting or burning through the tube walls. Almost all aluminum brazing to date has been confined to small parts done in molten salt baths. The size of the NERVA extension and the cleaning problems associated with the use of molten salt make brazing an impractical tube joining method. It is realized that other tube configurations which could be joined satisfactorily are under consideration, but development programs to determine the optimum configuration and assembly procedure will be required.

On the other hand, brazing has been proven to be a reliable method of joining a stainless steel tube bundle on the Titan family and other competitive programs, and no new fabrication problems are anticipated. Some investigation into the optimum tube-to-flange joint will probably be required.

With the above-mentioned assumption in mind, the "one-zero" method was used to rate the three concepts on various failure modes, and thus arrive at a preliminary quantitative comparison of reliability. As can be seen, the preliminary ratings are such that all three concepts must be considered as being essentially equal from a reliability standpoint at present.

In order to conduct a more detailed comparison, thermal and stress analyses of the three concepts must be conducted, particularly of the skirt-to-skirt extension joint (forward flange) area, and the primary stresses must be defined. Stresses and material strengths can then be compared and a more realistic comparison derived. The FMAs for the three concepts and the reliability comparison will be revised as new information becomes available.

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CLASSIFICATION CATEGORY
UNCLASSIFIED
U. M. Bryan 10/1/69
CLASSIFYING OFFICER DATE

3.73

RELIABILITY COMPARISON OF GAS AND CRYOGENICALLY COOLED AND FIBROUS GRAPHITE SKIRT EXTENSIONS

Problem Area	Gas Cooled	Rating	Cryogenically Cooled	Rating	Fibrous Graphite	Rating	Remarks
1. Fabrication	1.a. Much previous experience with 347 stainless tube bundle concept. NERVA extension is longer and larger diameter, but no new fab. problems expected. Good NDT methods for detection of discrepancies established. Flange-to-tube joint is new concept. Fitup, weld, and braze problems possible. Good NDT methods available.	1 1	Very little previous aluminum tube bundle fab. experience. Able-O combustion chamber was relatively heavy wall tube all welded. Optimum tube configuration and joining methods must be investigated and developed. Good NDT methods for detection of discrepancies are available.	0 1	No previous experience making fibrous graphite parts this size. Large ablative tape-wrapped parts made for 260" solids successfully, but tape-wrap component was cemented into solid metal or honeycomb can which was load carrying member. Optimum fab. method must be determined and feasibility of making acceptable parts demonstrated. Ability of NDT methods to detect injurious discrepancies questioned.	0 0	Ply orientation, particularly in the flange area, is critical in the AG Carb extension because of the vast difference in strength of the material ‖ and ⊥ the plies. (Tensile ‖ plies ~11,000 psi, tensile ⊥ plies ~600 psi, interlaminar shear ~1300 psi). Preference is given to cryo-cooled over AG Carb because of more effective NDT methods.
2. Flange Area a. Hot Gas Seal Leakage	2.a. (Flange-to-flange, welded, external). (1) Seal-to-flange weld separation caused by differential expansion, plus vibration induced bending fatigue, plus flange distortion. Flange distortion effect relatively minor.	1 1	2.a. (Flange-to-flange mating surfaces). (1) Differential expansion of flanges causes seal rubbing. (2) Flange distortion may unload seal and allow leakage. (3) Permanent deformation of seal allows leakage. (4) Bolt stress relaxation due to operating temperature, flange distortion, vibration.	0 1	2.a. (Flange-to-flange mating surfaces) (1) Differential expansion of flanges causes seal rubbing. (2) Flange distortion may unload seal and allow leakage. (3) Permanent seal deformation allows leakage. (4) Bolt pre-stress relaxation due to operating temperature, flange distortion, vibration. (5) Permanent flange deformation allows leakage.	0 0	Theoretical temperatures in joint areas, and predicted flange movements must be determined. Since welded seal of gas cooled extension must be installed after assembly of extension to skirt, adequate welding and NDT facilities must be available at launch site or special shipping precautions must be taken to ship larger assembly.
	Page Total	4		2		0	

Enclosure (1)
7850-M-291

RELIABILITY COMPARISON OF GAS AND CRYOGENICALLY COOLED AND FIBROUS GRAPHITE SKIRT EXTENSIONS (continued)

Problem Area	Gas Cooled	Rating	Cryogenically Cooled	Rating	Fibrous Graphite	Rating	Remarks
2. Flange Area (cont) b. Attach Bolt Failure	2.b.(1) Inertia and vibration during boot phase. Heavy part.	0 0	2.b.(1) Inertia and vibration during boost phase. Intermed. weight.	1 0	2.b.(1) Inertia and vibration during boost phase. Light part.	1 1	Theoretical temperatures in joint areas and predicted flange movements must be determined.
	(2) Differential growth and distortion of flanges, side loading, vibration, during NERVA operation.		(2) Differential growth and distortion of flanges, side loading, vibration, during NERVA operation.		(2) Differential growth and distortion of flanges, side loading, vibration during NERVA operation.		
	(3) Severe temperature gradient in joint.		(3) Least severe joint temperature gradient of three.		(3) Most severe temperature gradient in joint.		
	(4) Long coolant gas inlet lines and torus add appreciably to vibration stresses in joint.		(4) Inlet and outlet lines and torus will add to vibration level in joint.		(4) No tubes or torus. Probable lower vibration stresses.		
	(5) Hot gas leak past seal lowers bolt strength below fatigue limit.	.5 1	(5) Hot gas leak past seal lowers bolt strength below fatigue limit.	.5 1	(5) Hot gas leak past seal lowers bolt strength below fatigue limit.	0 0	
c. Tubes Fail to Contain Coolant Fluid	2.c.(1) Flange distortion, firing vibration, and side loading during firing.	1 0	2.c.(1) Flange distortion, firing vibration, and side loading during firing.	0 0	2.c.(1) No coolant required.	1 1	
d. Inlet-to-Torus, Torus-to-Torus, or Torus-to-Flange Weld Failure	2.d.(1) Inertia and vibration boost phase.	0 0	2.d.(1) Inertia and vibration during boost phase.	1 0	2.d.(1) Not required.	1 1	
	(2) Expansion of inlet lines, flange distortion, and vibration during NERVA firing.		(2) Unequal contraction of inlet and outlet lines, flange distortion, and vibration during NERVA firing.				
	(3) High vibration levels expected from inlet lines during NERVA firing.		(3) Outline line could be long and add appreciably to vibration stress.				
	Page Total	2.5		3.5		6	

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Enclosure (1)
7650:N:9291

RELIABILITY COMPARISON OF GAS AND CRYOGENICALLY COOLED AND FIBROUS GRAPHITE SKIRT EXTENSIONS (continued)

Problem Area	Gas Cooled	Rating	Cryogenically Cooled	Rating	Fibrous Graphite	Rating	Remarks
2. Flange Area (cont) e. Flange Fails to Support Body of Extension	2.e.(1) Boost phase inertia and vibration.	0 0	2.e.(1) Boost phase inertia and vibration.	1 0	2.e.(1) Boost phase inertia and vibration.	1	
	(2) Flange distortion during NERVA operation.	0 .5	(2) Flange distortion during NERVA operation.	1 1	(2) Flange distortion during NERVA operation.	.5 0	
	(3) Vibration and side loads during NERVA operation.	.5 1	(3) Vibration and side loads during NERVA operation.	.5 1	(3) Vibration and side loads during NERVA operation.	0 0	
	(4) Burn-through of tubes or braze joint at "hot spots".	1 0	(4) Burn-through of tubes or joint at "hot spots".	0 0	(4) Chemical reaction between graphite and H_2 reduces wall thickness.	1 1	
3. Body of Extension a. Hot Gases are not Directed along Flight Axis	3.a.(1) Distortion or warpage of tube bundle.	.5 0	3.a.(1) Distortion or warpage of tube bundle.	.5 0	3.a.(1) Distortion or warpage of extension body.	1 1	High graphitization temperature of AG Carb (5460°R) exceeds operating temperature.
b. Hot Gases are not Contained by Extension Body	3.b.(1) Burn-through of tubes or braze alloy.	0 0	3.b.(1) Burn-through of tubes or joint.	1 0	3.b.(1) Chemical reaction between braphite and H_2 reduces wall thickness.	1 1	
	3.b.(2) Failure of tube at braze joint, or separation of braze joint, from vibration stress.	.5 1	3.b.(2) Failure of tube or joint from vibration stress.	.5 1	3.b.(2) Failure of extension wall from vibration stress.	0 0	
	Page Total	5		7.5		8.5	
	Grand Total	11.5		13		14.5	

Enclosure (1)
7850:M0291

M E M O R A N D U M

TO: L. D. Johnson DATE: 9 October 1969
7850:M0299

FROM: R. D. Zonge

SUBJECT: Reliability Evaluation of Three SSCV Concepts

COPIES TO: W. M. Bryan, J. F. Mason, J. H. Ramsthaler, J. C. Toboni, E. J. West, Section 7850 Personnel

ENCLOSURE: (1) Functional Descriptions and Sketches of Three SSCV Concepts

(2) Procedure for Estimating Relative Reliabilities

(3) "One-Zero" Method of Design Selection

INTRODUCTION

This analysis was performed to establish which of the three proposed SSCV concepts was inherently most reliable and, therefore, should be developed for eventual inclusion into the NERVA Program. Specific reliability values were not determined.

The support structure coolant valve proportions a flow of approximately 21 lb/sec of LH_2 between the stem coolant line and a by-pass. All three valves have been designed so that flow to neither stems nor by-pass can be shutoff. The critical mode of failure of this component is to provide an improper proportion of coolant to the stems.

A functional description and a sketch of each concept are included as Enclosure (1).

SUMMARY

Relative reliability rankings of the three support structure coolant valve design concepts were determined. The methods used were: 1) a summation of the relative failure rates using the FMA's developed by Design Engineering, and 2) a "one-zero" relative rating of the three concepts on 15 general criteria. Both methods ranked the concepts in the following order of reliability preference:

1. Ball Valve
2. Flodi Valve
3. Rotary Blade Valve

RECOMMENDATIONS

1. Comparing the results of both ratings, it can be seen that the valves are ranked in the same order by both analyses. It is recommended that both the ball and "Flodi" valves be considered for further development.

3.77

2. The "cylinder-sphere" failure mechanism of the ball valve could be eliminated by omitting the cylindrical sleeve welded into the ball. Either a ball with a straight through bore, or one partially hollowed out similar to the Apollo ball, could be used.

3. The dynamic seal at the by-pass outlet should be eliminated as it serves no purpose.

4. The LH_2 inlet on the "Flodi" valve could be cut off to permit removal of the inlet housing from the valve without removing the valve from the engine assembly (refer to note in Table II).

ANALYSIS

Design Engineering generated FMA's for each concept and rated each failure mechanism with the procedure of Enclosure (2). The failure mechanisms and their corresponding ratings were reviewed by Reliability, and where necessary, discussions were held with Design Engineering to produce a mutually agreeable FMA for each valve concept. A tabulation of the failure mechanisms for each concept and their relative "failure rate potentials" is given in Table I.

Fifteen design criteria were selected for comparison of the three valve concepts, and the "one-zero" method of determining relative reliabilities was applied in accordance with the procedure of Enclosure (3). Table II lists the criteria and the resultant numerical ratings as agreed to by Design Engineering and Reliability.

R. D. Zonge

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CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE

3,75

TABLE 1

FAILURE SUMMARY

"Mode"	ROTARY BLADE "Failure Rate"	FLODI "Failure Rate"	BALL "Failure Rate"
Inlet Housing Failure	2.20	2.15	-
Outlet Housing Failure	2.20	2.65	1.80
Leaks - Hsg to Hsg Joint	1.63	1.63	1.63
Leaks - Joint	2.50	4.10	4.40
Binding - Inlet Hsg Buckles	1.60	1.90	-
Binding - Outlet Hsg Buckles	1.60	2.10	1.95
Failure - Blade, Ball, Cone	1.70	2.10	2.40
Brg. Fail - Blade, Ball, Cone	1.80	1.70	1.73
Bearing Failure	2.05	-	1.80
Binding - Shaft Seal	2.80	2.80	-
Leaks - Shaft Seal	2.57	3.07	-
Bearing Retainer Failure	1.00	-	1.00
Fail Actuator Coupling	1.40	2.00	-
Fail Cover	-	-	1.95
Fail Center Bolt	1.15	-	-
Fail Center Bolt Seal	5.20	-	-
Fail Actuator Bearing	1.55	-	-
Fail Actuator Gear	2.05	-	-
Fail Actuator Brg. Retainer	1.00	-	-
Fail Shaft Seal Retainer	1.00	-	-
Fail Hsg. Actuator Joint	-	1.20	-
Outlet Housing Deflection	-	1.60	-
Inlet Housing Deflection	-	1.60	-
Cone Deflection	-	1.80	-
Cylinder - Sphere Failure	-	-	2.18
Binding Sphere	-	-	3.88
TOTALS:	37.00	32.40	24.72
Design Preference	Third	Second	First

TABLE II

DESIGN CRITERIA	CONCEPT	1			2			3			
	DESCRIPTION	BLADE			"FLODI"			BALL			
	COMBINATION	1	2	3	1	2	3	1	2	3	
1. General Compexity		0	0		1		1		1	0	
2. Fabrication Difficulties		1	1		0		1		0	0	
3. Seals & Leak Paths		0	0		1		0		1	1	
4. Contamination Sensitivity		0	0		1		0		1	1	
5. Number of Moving Parts		0	0		1		0		1	1	
6. Susceptibility to Rupture and/or Pressure Induced Binding		0	0		1		0		1	1	
7. Susceptibility to Thermal Stress and/or Binding		0	0		1		0		1	1	
8. Susceptibility to Wear		0	0		1		0		1	1	
9. Torque Requirement		0	0		1		0		1	1	
10. Tolerance Requirements		1	1		0		1		0	0	
11. Failure Position			-			-			-		None
12. Improper Assembly		0	0		1		1		1	0	
13. Ease of Maintenance		0	0		1*		0		1	1	*Clip inlet t[illegible] permit in plac[illegible]
14. Control Sensitivity		1	1		0		1		0	0	
15. Vibration Sensitivity		0	0		1		0		1	1	
TOTALS:			6			16				20	
PREFERENCE			Third			Second				First	

3-2

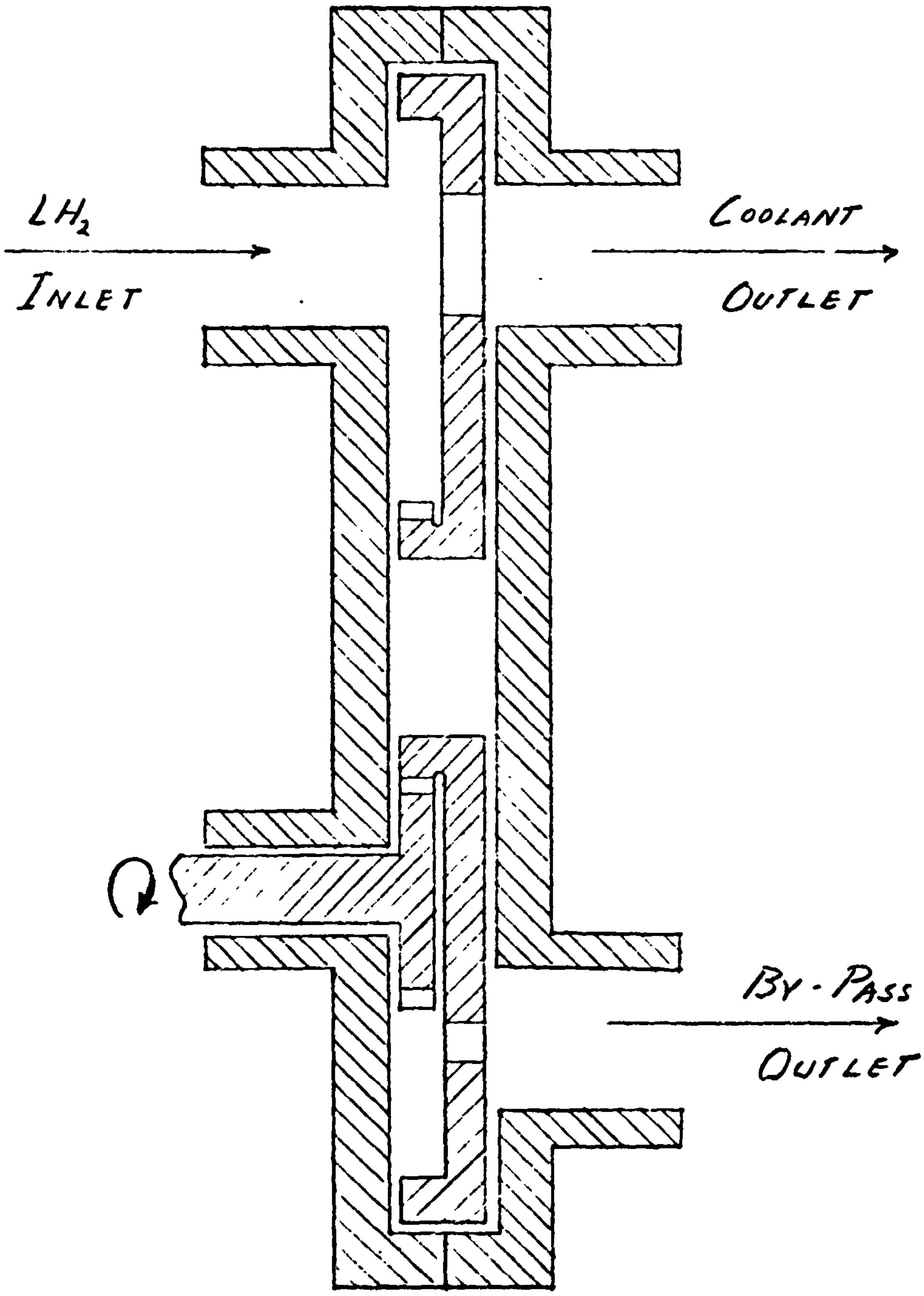
CONCEPT #1 - ROTARY BLADE

A disc with various sizes and shapes of apertures is rotated between two relatively flat circular housing halves. One half contains the LH_2 inlet, which is positioned off center, and the other includes the coolant and by-pass outlets with the coolant outlet positioned on the same center line as the LH_2 inlet.

Apportionment of flow is accomplished by rotating the disc to position the appropriate apertures in front of the coolant and by-pass outlets. Two spur gears are used to rotate the disc. Mechanical stops are provided to limit disc rotation within desired extremes.

Most probable mode of failure is binding of the disc due to warpage or distortion or freezing of the bearings. Failure of the valve with the disc in any position will allow some coolant flow since the coolant outlet port is never blocked.

CONCEPT 1, ROTARY BLADE



ENCLOSURE (1)
7850:M0299

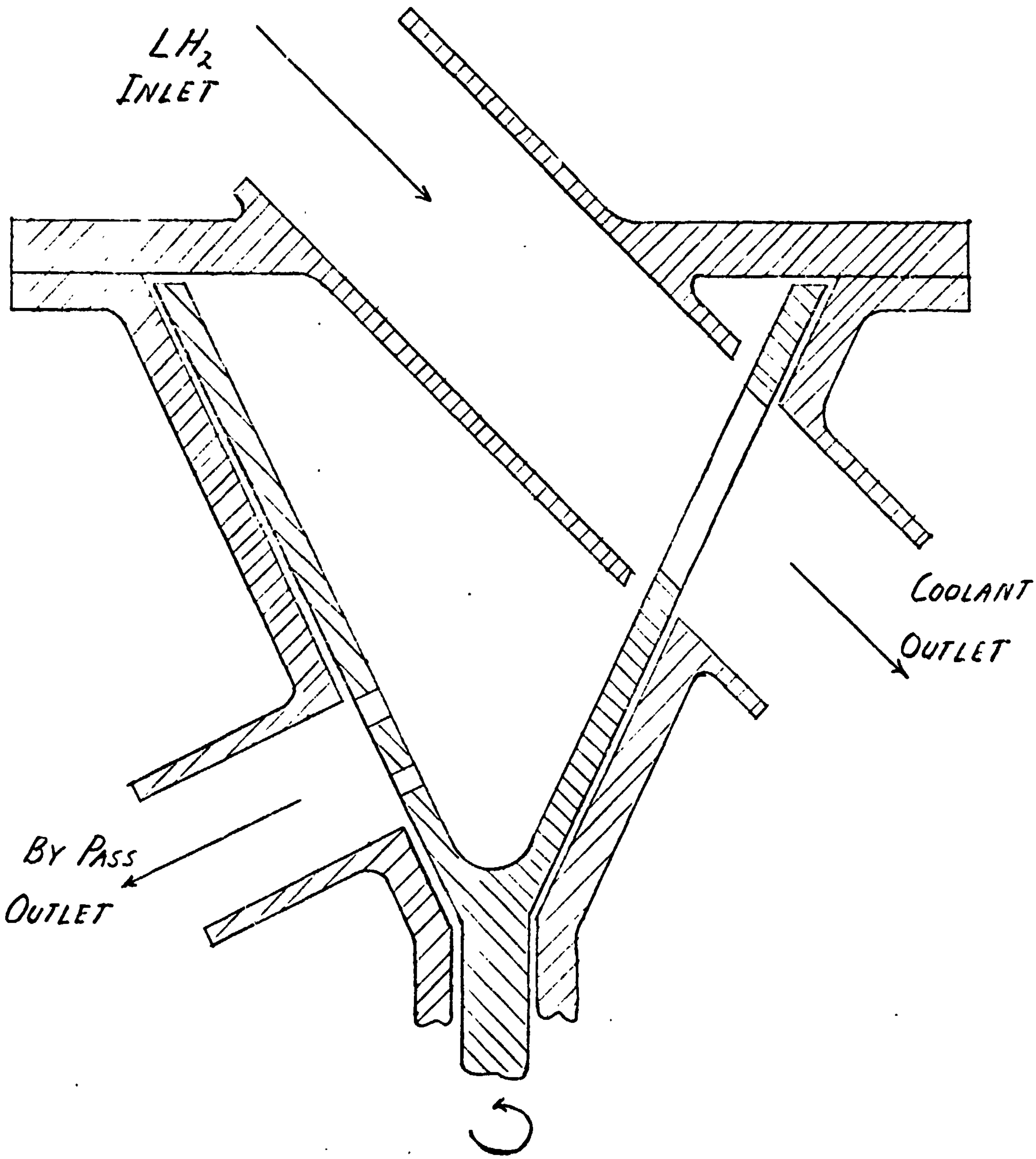
CONCEPT #2 - FLODI VALVE

A conical member containing a number of various sizes and shapes of apertures through the wall is rotated within a conical housing which contains the LH_2 inlet and the coolant and by-pass outlets. The LH_2 inlet is in the housing cover with the coolant outlet located on the same centerline.

Apportionment of flow is accomplished by rotating the movable cone to position the appropriate apertures in front of the coolant and by-pass outlets. The small diameter of the cone is extended into a shaft through which the rotation of the actuator is transmitted.

Most probable mode of failure is binding of the movable cone. Failure of the valve with the movable cone in any position will allow some coolant flow since the coolant outlet port is never blocked.

CONCEPT 2 FLODI VALVE



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ENCLOSURE (1)
7850:MG299

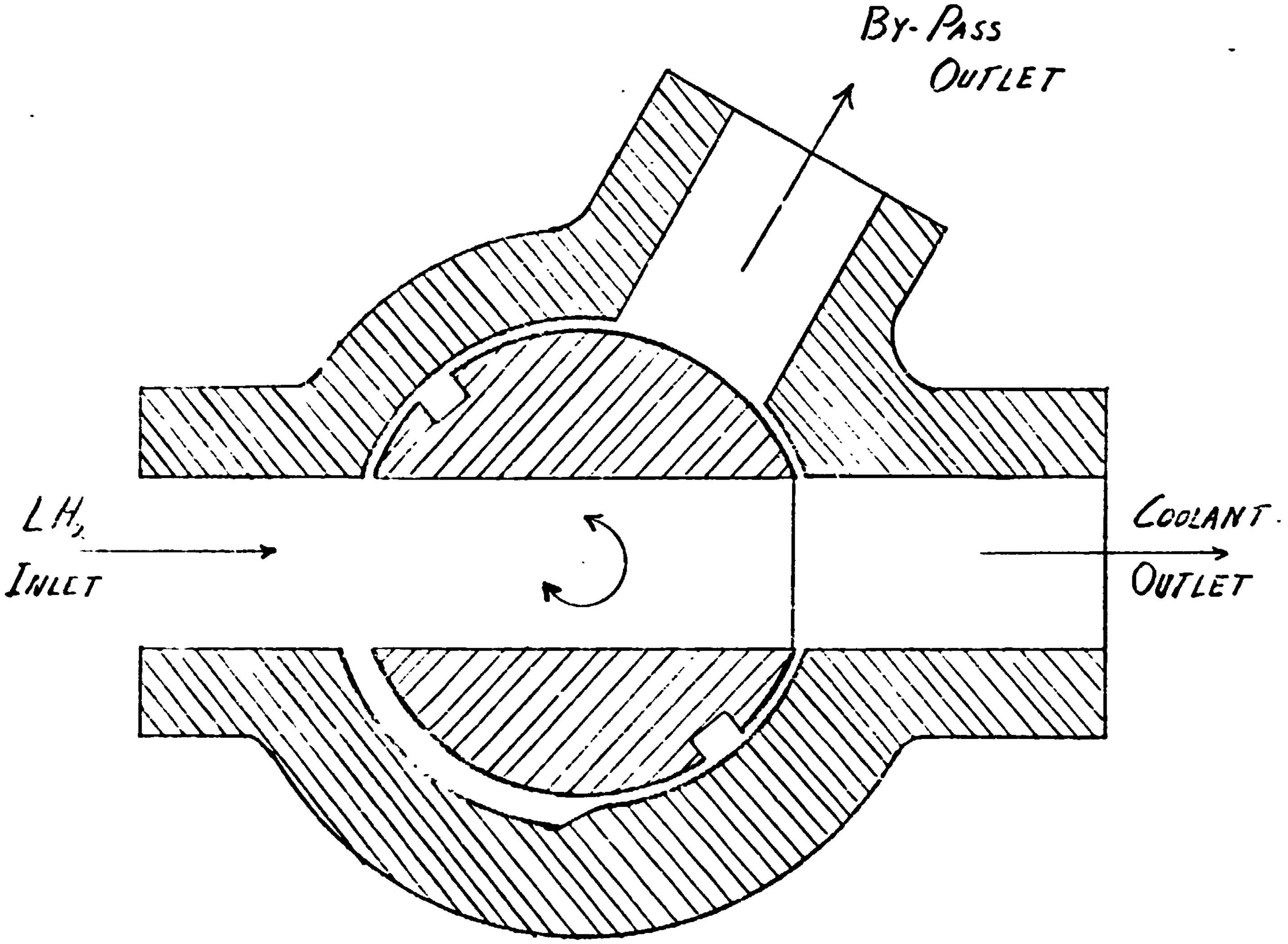
CONCEPT #3 - BALL VALVE

A ball with a bore through it is rotated within a housing containing the LH_2 inlet and the coolant and by-pass outlets. The LH_2 inlet and coolant outlet are positioned on the same center line.

Apportionment is accomplished by rotating the ball about an axis perpendicular to the bore and inlet and outlet center lines.

Most probable mode of failure is binding of the ball due to freezing of the bearings during initial cooldown or deflection of shafts during partially closed operations. Failure of the valve with the ball in any position will allow coolant flow. The ball contains a circumferential groove in a location such that LH_2 flows around the groove and into the coolant outlet when the bore is positioned to direct full flow to the by-pass outlet.

CONCEPT 3, BALL VALVE



PROCEDURE FOR ESTIMATING RELATIVE RELIABILITY

This is a method of establishing the relative reliability of each proposed design concept of a mechanical component during the conceptual design phase. It qualifies and combines the judgements of Design and Reliability engineers into a single value so as to provide a reliability criterion for design selection.

The method requires that a failure mode analysis be conducted on each candidate design by a qualified design engineer. In performing the analysis, the engineer takes into consideration all environments and operating conditions encountered during the life cycle of the component, and rates each failure mode on its failure potential in accordance with the table below. In the table, the alpha character designates the success potential of the design in decreasing magnitude from A through D, and the numerical designation indicates the degree of discovery and control through inspection or test methods. The degree of controllability is indicated by the numeric designator which decreases in magnitude from 1 through 4. The individual potentials for failure are then combines into a single rating.

The rating of a component obtained by this method is of value only in relation to similar ratings of other design concepts for the same component where the analysis has been carried to the same detail level. It is best for an individual analyst to rate all concepts of a design to assess relative success or failure potential.

"FAILURE RATE POTENTIAL" VALUES

		CONTROL RATING			
		1	2	3	4
DESIGN RATING	A	1	2	3	4
	B	2	4	6	8
	C	3	6	9	12
	D	4	8	12	16

Two or more analysts will generally rank the concepts in the same order, but will not generally arrive at identical ratings for failure potential.

3.57

"ONE-ZERO" METHOD OF ESTIMATING RELATIVE RELIABILITY

This is a method of comparing the relative merits of a number of similar concepts in regard to a common characteristic. As an estimate of relative reliability, it combines the judgement of Design and Reliability Engineering and results in a numerical comparison of relative reliabilities.

The method requires the selection of a number of criteria affecting the reliability (or other characteristic to be compared) of the concepts involved. All essential criteria should be included. Each candidate concept is then compared with each other concept in respect to each criterion. Only two concepts are compared in respect to one criterion at a time. The better concept is given a one (1), and the other a zero, regardless of the degree of superiority of one over the other. In cases of an absolute tie, e.g., the criterion could be "number of joints that could leak externally", and the two concepts being compared had the same number,siz, and type of joints, each could be given a rating of 0.5. However, in almost all cases a decision should be forced.

When each concept has been compared with each other concept in respect to all criteria the total ratings will indicate the relative merits of the concepts. The concept with the most "ones" and therefore the highest rating being the most desirable.

MEMORANDUM

TO: L. D. Johnson DATE: 22 October 1969
7850:M0311

FROM: J. E. Jensen

SUBJECT: Reliability Evaluation of Three Turbine Block Valve (TBV) Concepts

COPIES TO: J. J. Beereboom, W. M. Bryan, D. Buden, J. M. Klacking, B. Mandell, J. F. Mason, J. H. Ramsthaler, E. A. Sheridan, J. C. Toboni, E. J. West, 7850 Personnel
NTO: W. H. Bushnell

REFERENCES:
(a) Butterfly TBV, P/N 1136745
(b) Gate TBV, P/N 1136827
(c) Poppet TBV, P/N 1136682

ENCLOSURES:
(1) Functional Description and Sketches of Three TBV Concepts
(2) Procedure for Estimating Relative Reliabilities
(3) One-Zero Method of Design Selection

Introduction

A reliability analysis was made of three proposed TBV configurations. They are schematically presented in Figures 1 through 3. The purpose of this analysis was to make a reliability comparison to establish which of the three TBV concepts was inherently most reliable and to provide input for the turbine feed system trade studies. The evaluation was based on the blocking ability of the valves only, since the actuation mechanism (pneumatic or electrical) has not been clearly defined.

The TBV blocks flow to the turbine inlet during pre-conditioning and engine cooldown and is open during normal operation of startup, steady state and shutdown. In addition, they provide for a rapid shutoff capability of the turbine drive gases isolating the turbine of a failed TPA. Critical failure modes of the component are: 1) premature closing, 2) failure to close within the required time, or 3) failure to open.

A functional description and a sketch of each concept are included as Enclosure (1).

Summary

The relative reliability rankings of the three turbine block valve concepts were determined. The methods used were: 1) a summation of the relative failure rates using modified FMAs developed by Design Engineering, and 2) a "one-zero" relative rating of the three concepts on 14 general criteria. The first method ranked the valves in the following order: 1) poppet, 2) butterfly, 3) gate; and the "one-zero" method ranked the concepts as follows: 1) butterfly, 2) poppet, and 3) gate.

3.89

Recommendations

1. Comparing the results of both reliability ratings revealed, the two most preferable concepts were the poppet and butterfly. It is therefore recommended that both the poppet and butterfly concepts be considered for further development.

2. The poppet valve should be designed with a snubbing device to slow the poppet travel just before making contact with the seat.

Analysis

Design Engineering generated FMAs for each turbine block valve concept and rated each failure mechanism in accordance with the procedure of Enclosure (2). However, the FMAs were generated for pneumatically actuated valves and those temperature-pressure characteristics required by the NERVA Hot Bleed Engine system. NRO has since been directed to design all valves with an electrical actuation mechanism. In addition, the NERVA Full Flow Engine concept was selected for development which significantly decreases the temperature of the turbine drive gas but also requires significant increase in pressure. It was therefore necessary to modify the FMAs per the new criteria. A tabulation of the like piece parts and their relative "failure rate potentials" is given in Table I.

The "one-zero" method of determining the relative reliabilities were applied to 14 design criteria in accordance with the procedure of Enclosure (3). Table II lists the design criteria and the relative ratings.

J. E. Jensen

J. E. Jensen
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

3.90

Table I
7850:M0311

TABLE I

FAILURE RATE POTENTIAL COMPARISON

Butterfly Valve	Failure Rate	Poppet	Failure Rate	Gate	Failure Rate
Valve Housing	2.25	Valve Housing	3.70	Valve Housing	3.55
Shaft	2.80	Shaft	2.15	Shaft	2.05
Butterfly Disk	2.50	Poppet	2.30	Gate	3.75
Radial Bearings	2.15				
Thrust Bearing	1.61				
Snap Rings	.50				
Bearing Retainer	.40	Seal Retainers	.80	Seal Retainers	.80
Main Seal	2.68	Main Seal	2.00	Main Seal	3.20
Anchor Bolt	1.63	Piston Shaft to Poppet	1.63	Monoball and Pin	1.63
End Covers	1.15	End Cover	1.00	Housing Cover	1.00
External Static Seal	.20	Static Seals	.40	Static Seals	1.20
Moisture Preventive Seals	.40				
Rotary Dynamic Seal	.70	Linear Dynamic	2.80	Shaft Seal Assembly	3.80
Spring (Seal)	.50				
Retaining Ring	.20				
Gear (Rotary)	.80	Rack	.80	Rack	.80
		Linear Dynamic Seal/Guide	1.53	Shaft Guide	1.20
	20.47		19.11		22.98

3.91

TABLE II

ONE-ZERO RELATIVE RELIABILITY

Design Criteria	Concept	1		2		3	
	Description	Butterfly		Poppet		Gate	
	Combination	1vs2	1vs3	2vs1	2vs3	3vs1	3vs2
1. General Complexity		0	0	1	0	1	1
2. Fabrication Difficulties		1	1	0	1	0	0
3. External Leakage		0	1	1	.5	0	.5
4. Internal Leakage		.5	1	.5	.5	0	.5
5. Number Moving Parts		0	0	1	.5	1	.5
6. Susceptibility to Rupture and/or Pressure Induced Binding		1	1	0	1	0	0
7. Susceptibility to Wear		1	1	0	0	0	1
8. Torque Requirement		1	1	0	1	0	0
9. Tolerance Requirements		1	1	0	1	0	0
10. Failure Position		.5	1	.5	1	0	0
11. Improper Assembly		0	0	1	.5	1	.5
12. Ease of Maintenance		0	0	1	0	1	1
13. Contamination Sensitivity		1	1	0	.5	0	.5
14. Vibration Sensitivity		0	0	1	1	1	0
Total		16		15.5		10.5	

3.92

CONCEPT #1 - BUTTERFLY

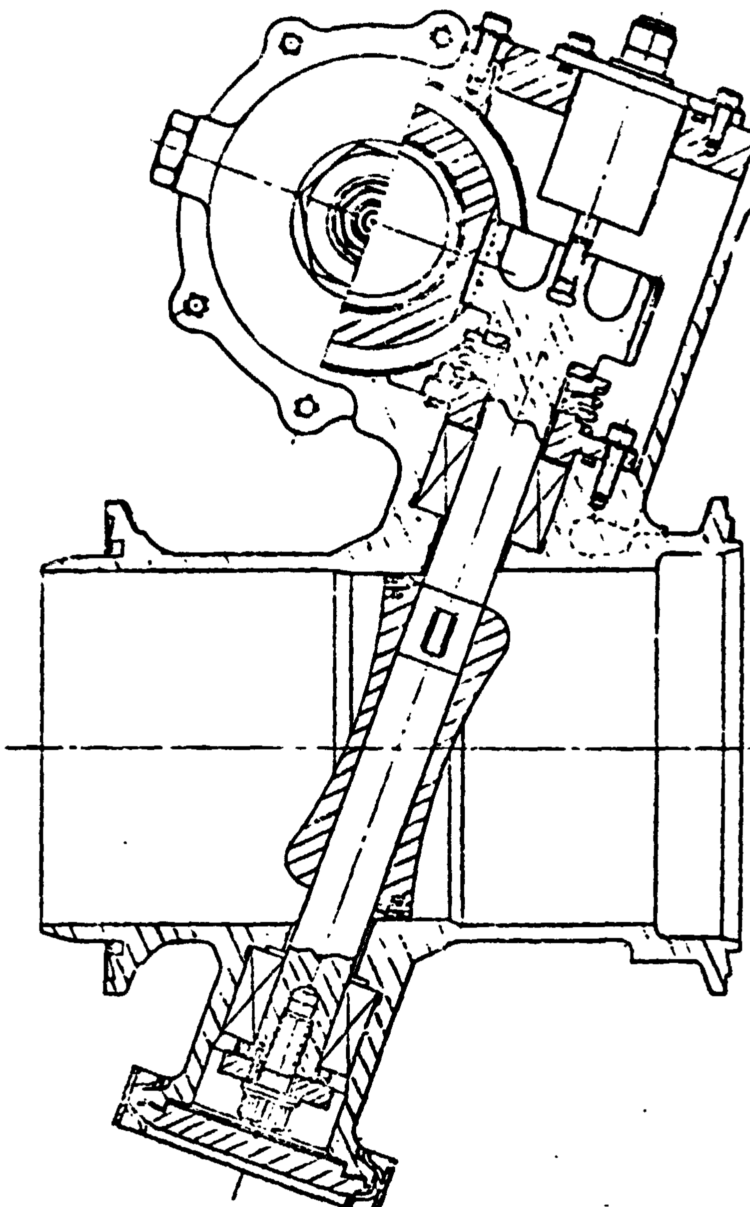
A butterfly disk rotated and supported on a one-piece shaft with a pinion gear located on the upper end. The shaft is tilted off perpendicular from flow approximately 15 degrees and passes completely through the flow passage. The shaft and butterfly is supported by two radial and one thrust bearing.

The valve is designed to provide binary flow control of the turbine drive gases and requires a rapid closing response.

The main seal (metal-to-metal) is provided by piston rings inserted into the butterfly disk contacting the interior surface of the bore.

Enclosure (1)
7850:M0311

Concept 1, Butterfly



3.94

CONCEPT #2 - POPPET

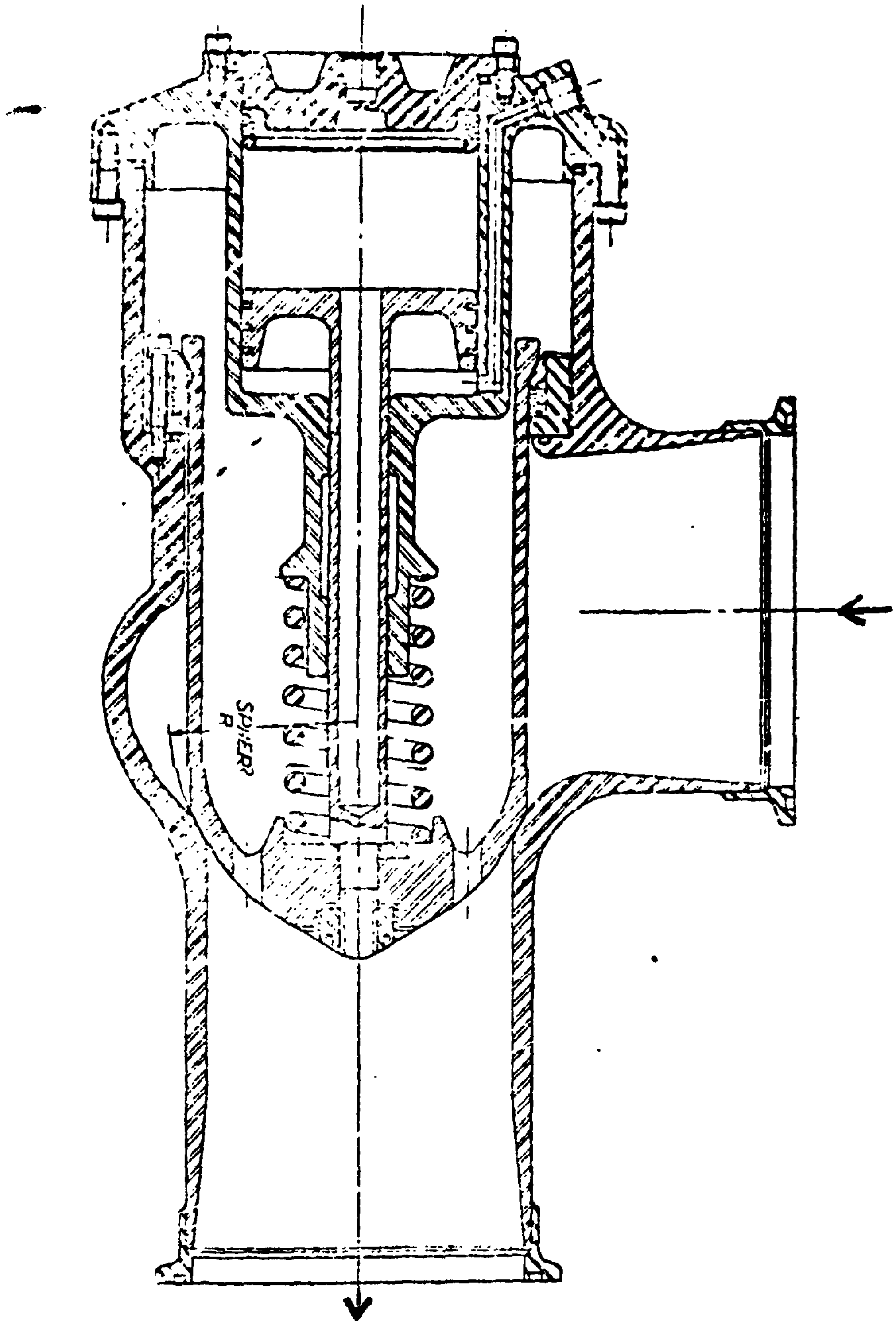
A linear motion poppet provides binary control of the turbine drive gases. The poppet and actuation mechanism is located in one leg of a "T" shaped housing. The poppet in the closed position blocks the outlet of the "L" shaped flow path. Simplicity is one of the virtues of this design as it is made up of only six major parts.

The main seal is provided by metal-to-metal contact of poppet seating against upstream edge of the housing outlet.

3.95

Concept 2, Poppet

Enclosure (1)
7850:M0311



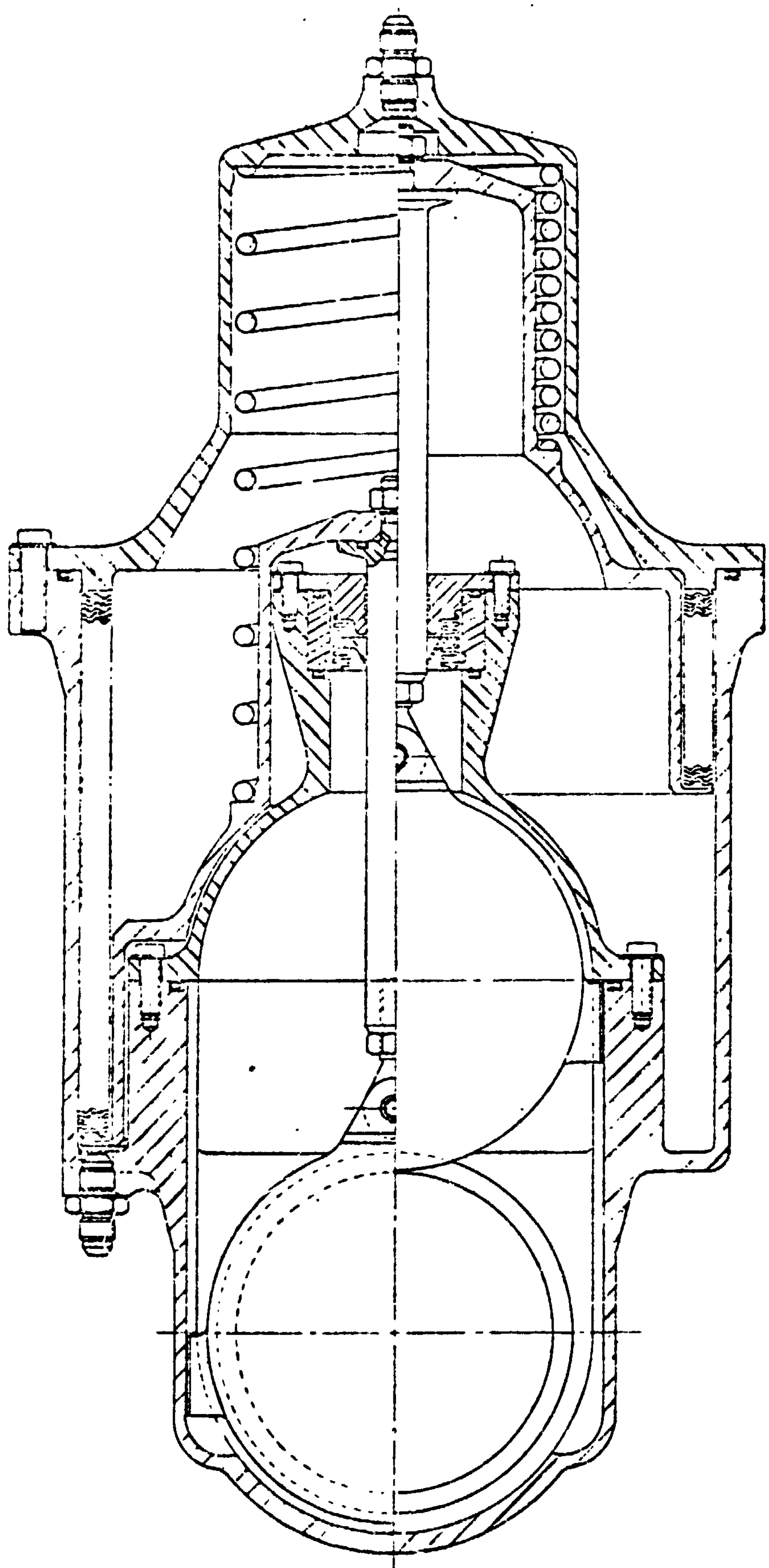
CONCEPT #3 - GATE

A circular wedge shaped gate attached by a monoball and pin to a linear motion shaft. The disk has a sliding guide on each side to provide the proper positioning of the gate during actuation and seating.

The main seal is provided by sliding the gate perpendicular to the flow into a wedge shaped slot in the housing bore. This is a metal-to-metal seal.

Concept 3, Gate

Enclosure (1)
7850:M0311



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PROCEDURE FOR ESTIMATING RELATIVE RELIABILITY

This is a method of establishing the relative reliability of each proposed design concept of a mechanical component during the conceptual design phase. It qualifies and combines the judgements of Design and Reliability engineers into a single value so as to provide a reliability criterion for design selection.

The method requires that a failure mode analysis be conducted on each candidate design by a qualified design engineer. In performing the analysis, the engineer takes into consideration all environments and operating conditions encountered during the life cycle of the component, and rates each failure mode on its failure potential in accordance with the table below. In the table, the alpha character designates the success potential of the design in decreasing magnitude from A through D, and the numerical designation indicates the degree of discovery and control through inspection or test methods. The degree of controllability is indicated by the numeric designator which decreases in magnitude from 1 through 4. The individual potentials for failure are then combined into a single rating.

The rating of a component obtained by this method is of value only in relation to similar ratings of other design concepts for the same component where the analysis has been carried to the same detail level. It is best for an individual analyst to rate all concepts of a design to assess relative success or failure potential.

"FAILURE RATE POTENTIAL" VALUES

		CONTROL RATING			
		1	2	3	4
DESIGN RATING	A	1	2	3	4
	B	2	4	6	8
	C	3	6	9	1[illegible]
	D	4	8	12	16

Two or more analysts will generally rank the concepts in the same order, but will not generally arrive at identical ratings for failure potential.

Enclosure (2)
7850:M0311

"ONE-ZERO" METHOD OF ESTIMATING RELATIVE RELIABILITY

This is a method of comparing the relative merits of a number of similar concepts in regard to a common characteristic. As an estimate of relative reliability, it combines the judgement of Design and Reliability Engineering and results in a numerical comparison of relative reliabilities.

The method requires the selection of a number of criteria affecting the reliability (or other characteristic to be compared) of the concepts involved. All essential criteria should be included. Each candidate concept is then compared with each other concept in respect to each criterion. Only two concepts are compared in respect to one criterion at a time. The better concept is given a one (1), and the other a zero, regardless of the degree of superiority of one over the other. In cases of an absolute tie, e.g., the criterion could be "number of joints that could leak externally", and the two concepts being compared had the same number, siz, and type of joints, each could be given a rating of 0.5. However, in almost all cases a decision should be forced.

When each concept has been compared with each other concept in respect to all criteria the total ratings will indicate the relative merits of the concepts. The concept with the most "ones" and therefore the highest rating being the most desirable.

3.100

MEMORANDUM

TO:	L. D. Johnson	DATE:	23 October 1969 7850:M0312
FROM:	R. D. Zonge		
SUBJECT:	Reliability Evaluation of Three PSOV Concepts		
COPIES TO:	J. J. Beereboom, W. M. Bryan, D. Buden, J. F. Mason, B. Mandell, J. M. Klacking, F. R. Pecoraro, J. H. Ramsthaler, E. A. Sheridan, J. H. Ramsthaler NTO: W. H. Bushnell		
ENCLOSURES:	(1) Functional Descriptions and Sketches of Three PSOV Concepts (2) Procedure for Estimating Relative Reliabilities (3) "One-Zero" Method of Design Selection		

Introduction

This analysis was performed to establish which of the three proposed PSOV concepts was inherently more reliable and therefore should be developed for eventual inclusion into the NERVA program. Specific reliability values were not determined.

The propellant shutoff is an on-off valve with allowable opening and closing times of three seconds. It is opened to allow flow of liquid hydrogen propellant to the TPA during the engine firing sequence (from prestart through pump tailoff) and closed at all other times to prevent loss of LH_2 from the main propellant tank. Critical modes of failure are: failure to open on command, inadvertent closing, and excess internal leakage.

A functional description and sketch of each concept is included as Enclosure (1). It is realized that the concepts reviewed were pneumatically actuated, and that the actuating mechanism will be changed to electrically powered systems. This change is expected to have very little, if any, effect on the reliability of the ball and flapper concepts. The relative reliability of the poppet, however, is expected to decrease because of the increased complexity of the electrical actuating mechanism.

Summary

Relative reliability rankings of the three propellant shutoff valve concepts were determined. The methods used were a summation of the relative failure rates using the FMAs developed by Design Engineering, and a "one-zero" relative rating, Enclosure (3), of the three concepts on 15 general criteria. Tables I and II present the results of these methods. Both methods ranked the poppet as the concept with the highest relative reliability.

Recommendations

1. From the results of both rating methods, it can be seen that the poppet concept has the highest relative reliability rating. The relative ranking of the other two concepts, however, differed in the two methods. It is recommended that all concepts be included in a redesign for electrical actuation, particularly since the electrical system is expected to adversely affect the reliability of the poppet concept.

2. It is strongly recommended that one engineer do the failure mode analyses for all concepts of one valve design. In this case, one engineer did the FMAs for the poppet and ball concepts, and another the flapper. A comparison of the anticipated failure rates of the three concepts (Table I) shows consistently higher rates for the flapper concept than the other two. This difference in evaluation is to be expected from person to person, and is the reason for the above recommendations.

3. If possible, a means of self-centering of the flapper on its seat should be incorporated into that concept.

4. In view of the presently proposed long coast periods, the consideration of plastic seats is recommended.

Analysis

Design Engineering generated FMAs for each concept and rated each failure mechanism with an alpha numerical code in accordance with the procedure of Enclosure (2). All failure modes pertaining to the method of actuation were disregarded because of the forthcoming change to electrical actuation. Also, no attempt was made to coordinate the FMAs and ratings between Reliability and Design Engineering because new FMAs will be generated for the electrically actuated concepts, and it is hoped that one design engineer will generate the FMAs for all concepts. Under the above conditions, the ranking of the poppet concept as having the highest relative reliability of the three concepts is valid, but the relative ranking of the flapper and ball concepts is questionable.

Fifteen design criteria were selected for comparison of the three valve concepts, and the "one-zero" method of determining relative reliability was applied in accordance with Enclosure (3). Table II lists the criteria and the resultant numerical ratings as agreed to by Design and Reliability.

R. D. Zonge

R. D. Zonge
Reliability
Reliability & Safety Analysis Section
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CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE

3,102

TABLE I

FAILURE MODE SUMMARY

FAILURE MODE	FAILURE RATES		
	Poppet	Ball	Flapper
Housing Failure	2.55	3.20	6.358
Bearing Failure		3.80	4.107
Poppet Failure	2.55		
Upper Flange Failure	2.20		
Lower Flange Failure	2.35		
Spring Failure	2.80		
Flapper Failure			5.193
Shaft Failure			4.195
Retainer Failure			2.10
Key Failure			3.055
Main Shaft Seal Failure			1.90
Inlet Flange Failure		2.80	
Main Seal Failure		2.25	
Ball Failure		1.90	
Flange Plate Failure (2)		3.90	
TOTALS	12.45	17.85	26.908

3,103

TABLE II

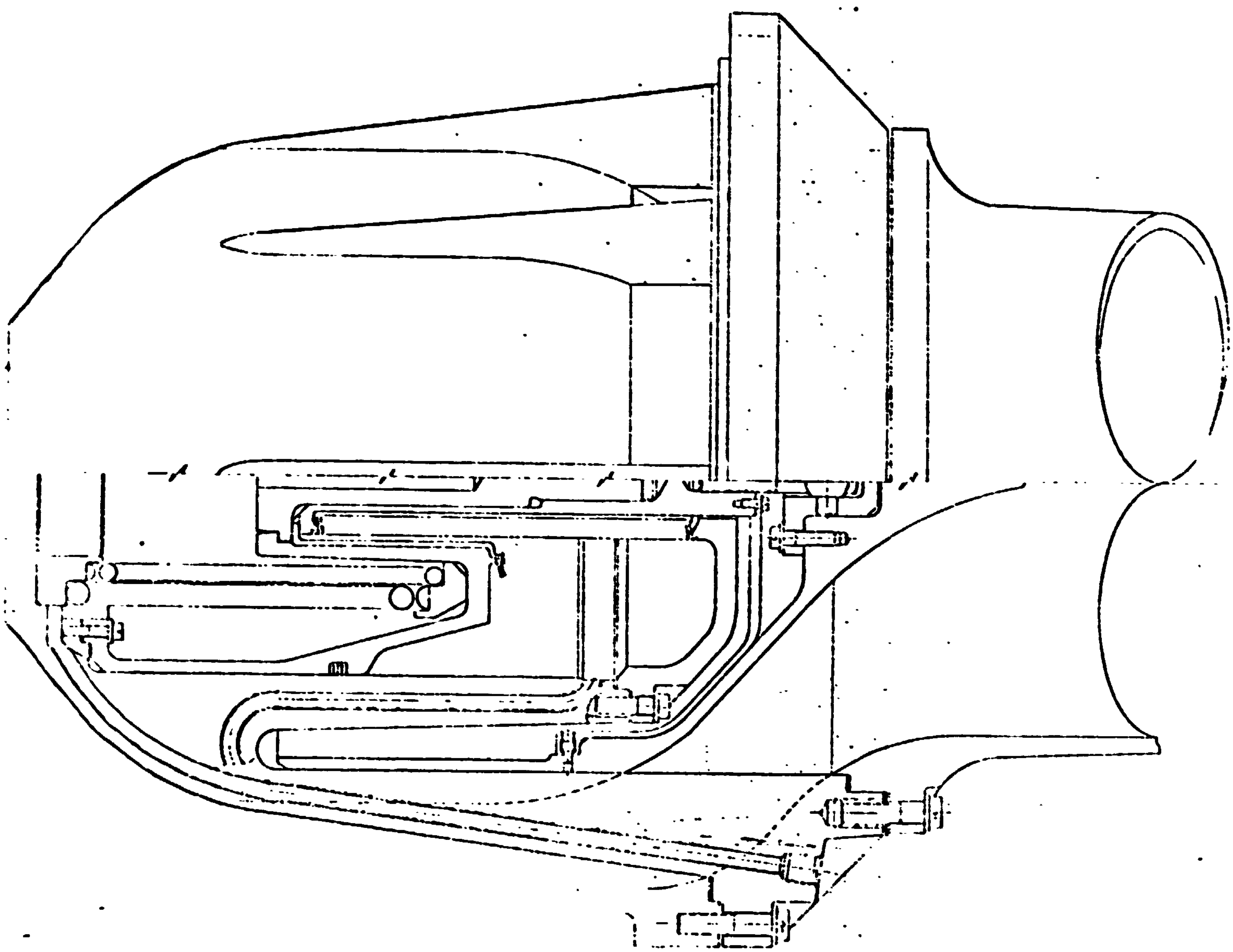
DESIGN CRITERIA	Concept No. / Description / Combination	1 Poppet: 1 vs 2	1 Poppet: 1 vs 3	2 Ball: 2 vs 1	2 Ball: 2 vs 3	3 Flapper: 3 vs 1	3 Flapper: 3 vs 2
1.	General Complexity	1	1	0	0	0	1
2.	Number of Moving Parts	1	1	0	1	0	0
3.	Fabrication Problems	1	1	0	0	0	1
4.	Torque Requirements	0	1	1	1	0	0
5.	Tolerance Requirements	1	1	0		0	0
6.	Improper Assembly	1	1	0	1	0	0
7.	Susceptibility to Wear	1	1	0	0	0	1
8.	Ease of Maintenance	0	0	1	0	1	1
9.	Vibration Sensitivity	1	1	0	0	0	1
10.	Contamination Sensitivity	1	1	0	1	0	0
11.	External Leakage	1	1	0	0	0	1
12.	Internal Leakage	1	1	0	1	0	0
13.	Susceptibility to Rupture and/or Buckling	1	1	0	0	0	1
14.	Susceptibility to Thermal Stress	1	1	0	0	0	1
15.	Susceptibility to Binding	0	0	1	1	1	0
16.	Ability to Seal Against Reverse Flow at TPA Discharge Pressure (None presently designed for this occurrence)	0	0	1	1	1	0
	TOTALS	25		12		11	

CONCEPT #1 - POPPET VALVE

A simple poppet design similar to a check valve in reverse. It open against tank pressure and closes with it. The most probable mode of failure, based on past experience with the XE engine, is internal leakage.

3,105

Concept 1 - Poppet Valve



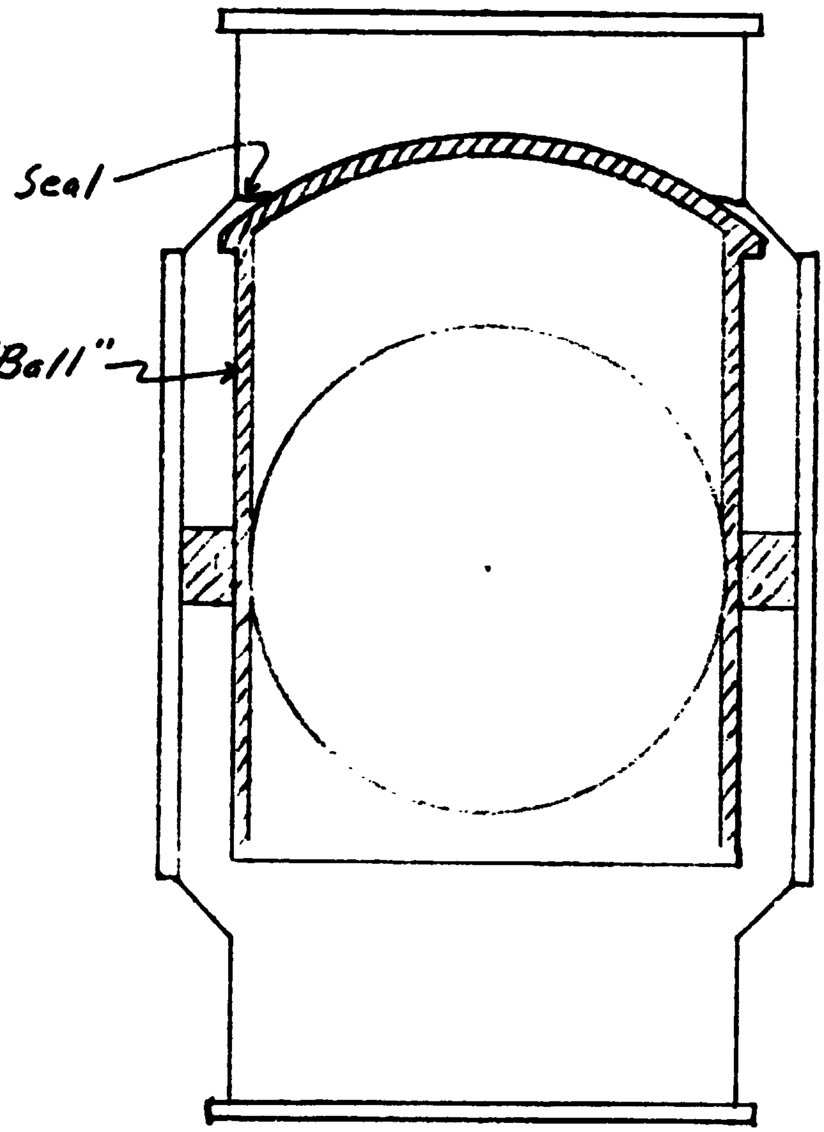
3,106

CONCEPT #2 - BALL VALVE

The "ball" in this valve is a spherical sequent which closes one end of a cylinder. The cylinder is supported and rotated about trunions mounted perpendicular to the cylindrical section axis. Also perpendicular to the axis of the cylinder and the trunions, two holes through the cylinder walls provide the propellant passage when the valve is opened. Sealing in the closed position is accomplished through contact between the spherical segment and a circular flexible seal. The surfaces of the seal and "ball" are in rubbing contact during opening and closing.

The most probable mode of failure is expected to be internal leakage.

Concept 2 - Ball Valve



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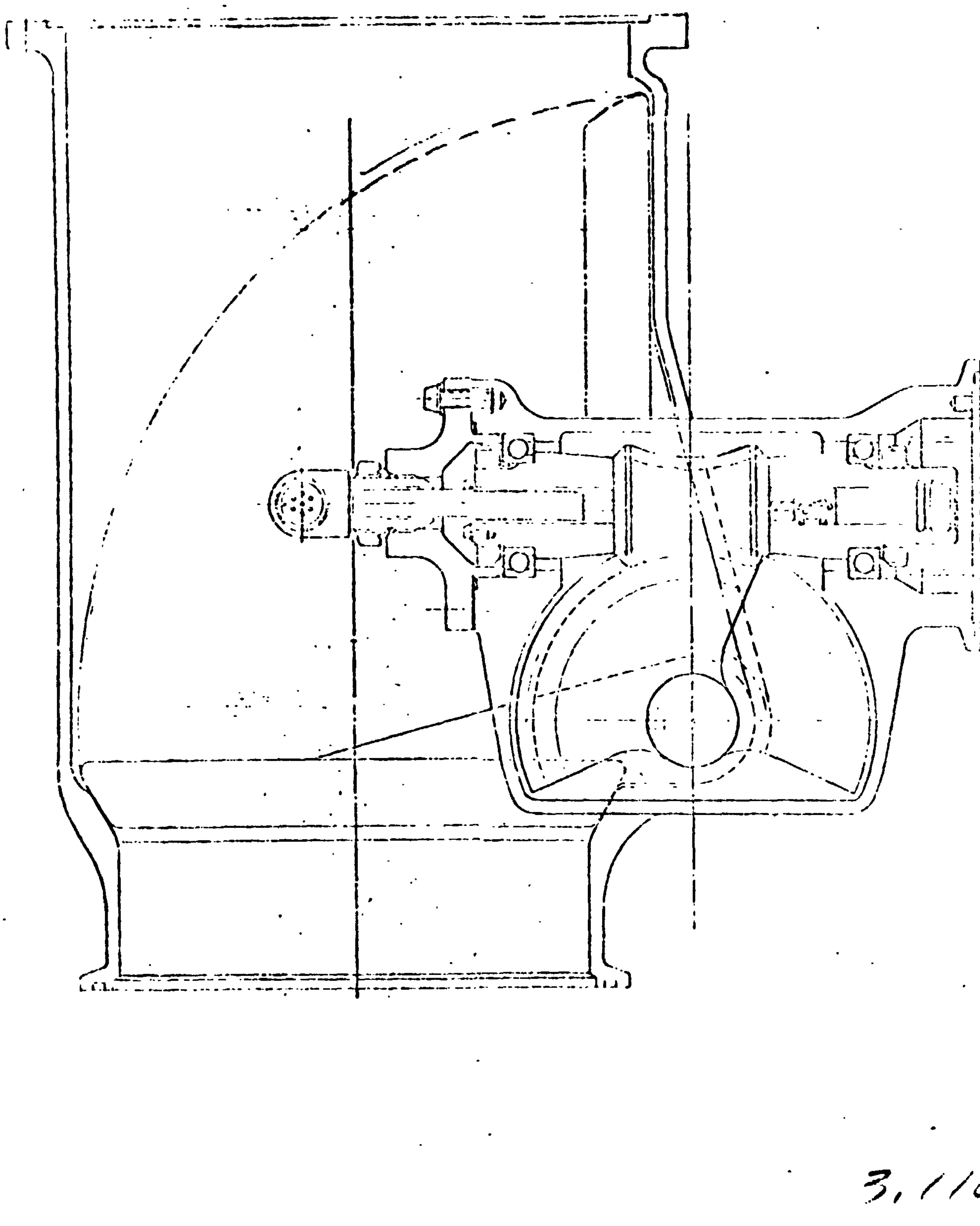
CONCEPT #3 - FLAPPER VALVE

Sealing in this valve is accomplished by a roughly round disc ("flapper") against a mating seat. The valve is opened by rotating the disc 90° around a shaft attached to one side. The valve opens against tank pressure and closes with it. The most probable mode of failure is expected to be internal leakage.

3.109

Concept 3- Flapper Valve



3,116

MEMORANDUM

TO: P. P. Ventura DATE: 30 October 1969
7850:M0318

FROM: W. M. Bryan

SUBJECT: Reliability Review of Hot Bleed Engine Trade Studies

COPIES TO: J.J. Beereboom, D. Buden, D.S. Duncan, R.V. Evleth, R.B. Glasscock, L.D. Johnson, J.M. Klacking, B. Mandell, I.L. Odgers, J.H. Ramsthaler, E.A. Sheridan, E.J. West, 7850 Personnel
NTO: W. H. Bushnell

REFERENCES:
(a) Memo 7010:124, dtd 10-16-69, P. P. Ventura to Distribution, Subject: Transmittal of Data Items S-054-009 and -005
(b) Trade Study Report - Structural Support Coolant Subsystem (SSCSS), dtd Sept. 69, Data Item S-054-007
(c) Memo, 7010:127, dtd 10-20-69, P. P. Ventura to Distribution, Subject: Transmittal of Data Item S-054-012

The referenced trade studies have been reviewed by Reliability and the following comments are submitted per your request:

a. Throttling Startup and Shutdown, Reference (a): Reliability assumptions are adequate for this study.

b. Structural Support Coolant, Reference (b): Section V.D., paragraph three, should be revised as follows:

"Concern for the single failure mode led to an investigation of SSCV reliability based on estimated valve and actuator failure rates. Results of the study indicated that unless the SSCV can be made an order of magnitude more reliable than is now estimated, a single SSCV actuator would have a 10 cycle mission reliability of 0.9985, a single SCV with redundant actuators would have a reliability of 0.99925, and any of three redundant SSCV actuator assembly systems would have a reliability of 0.99997. The absolute accuracy of these reliability estimates may be questioned, but it is obvious that to achieve the NERVA engine mission reliability goal of 0.995 a redundant SSCV system is required. It is therefore recommended that a redundant SSCV system be used.

CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE 10/31

W.M. Bryan
W. M. Bryan, Supervisor
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

3.1.1

M E M O R A N D U M

TO: P. P. Ventura DATE: 31 October 1969
7850:M0321

FROM: J. H. Ramsthaler

SUBJECT: Safety and Reliability Analysis Review of Trade Study S-054-012

COPIES TO: J. J. Beereboom, W. E. Campbell, B. Mandell, J. M. Klacking, C. F. Leyse, D. F. Vanica, Section 7850 Personnel

REFERENCE: (a) Memo 7010:127, P. P. Ventura to Distribution, Subject: Final NRO Review of Propellant Feed System Data Item S-054-012, dated 20 October 1969

(b) Memo 7850:M0105, D. S. Duncan to Distribution, Subject: Safety Requirements Applicable to Current Design and Trade Studies, 25 March 1969

A preliminary review has been made of trade study S-054-012 per your request in Reference (a). The following summarizes the review:

A. RELIABILITY

The reliability analyses appear very good. However, because of the limited time available for review of this detailed study it is not possible to concur or disagree with the conclusions.

To obtain effective Reliability input into studies such as this, the review must be initiated prior to the time the report is in final print. The normal progression should be to initiate the reliability review of concepts as they are undergoing engineering analysis. Documentation can be provided to the trade study engineer to be used similar to other engineering input. The final Reliability review can then be accomplished quickly with the initial studies having already been accomplished.

B. SAFETY

The safety analyses in this report are not satisfactory. The studies consider crew safety, but do not analyze safe disposal of the engine an equally important item. Crew safety is assessed numerically by assuming the crew is safe if no failures occur or if only one leg of a redundant system fails.

Parametric studies are conducted on the case of one failure in a redundant leg assuming the engine must complete the burn in process and an alternate recovery mode is available at the completion of the burn. The burn at which the alternate recovery can be effected is incremented from 0 to 10 using the synthetic reliability mission to determine changes in crew safety probability.

None of the above assumptions are valid for crew safety analysis. Any

3,112

failure or combination of failures which abort a mission during a burn do not necessarily cause an unsafe crew condition. If the failures do not directly harm the crew or damage the spacecraft the crew may be separated from the failed engine and safely returned depending on mission location at the time of failure. It is, therefore, necessary to conduct safety studies using defined missions.

There is no ground rule that an automatic abort is initiated with the failure of one component in a redundant system. Again this depends on position and if an abort were deemed advisable the engine would be returned to the emergency mission for completion of the burn for crew recovery.

The subject report did not address itself to changes in the number of single failure modes in the various configurations. These are very important in safety analysis since safety takes the position that while probabilistic reliability analysis is a good decision making tool the failure rates are not absolute. If a system is redundant there is time to take corrective action for safety. There is no corrective action time for a single point failure and these must be itemized in detail and the number of these compared between the various candidates.

A more detailed discussion of safety as it applies to engine design and the trade study activities is presented in Reference (b).

RECOMMENDATIONS

Because of the aforementioned problems with the safety write-up, it is recommended that all references to safety be removed from this trade study. It does not appear worthwhile to spend the additional time to prepare a new safety analysis, and it is recommended the report be issued as a non-management approved study. It is not felt management approval should be given to this trade study without a thorough safety analysis.

J. H. Ramsthaler, Manager
Reliability & Safety Analysis Section
Nuclear Rocket Operations

APPROVED:

J. J. Beereboom, Manager
Systems Department
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE

3.115

MEMORANDUM

TO: R. A. Henderson

DATE: 7 November 1969
7850:M0328

FROM: C. T. Lang

SUBJECT: Reliability Input to Trade Study #1001

COPIES TO: J. J. Beereboom, W. M. Bryan, B. Mandell, J. H. Ramsthaler, S. A. Varga, Section 7850

REFERENCES:
(a) Memo 7850:M0213, dtd 7-24-69, R. E. Lavond to R. A. Henderson, Subject: Acceptance Test Reliability Assessment
(b) Memo 7810:1776M, dtd 9-3-69, R. A. Henderson to S. A. Varga, Subject: Acceptance Test Trade Study #1001, Status of
(c) Memo 9670:TS104R, dtd 10-15-65, A. J. Mihanovich to R. F. O'Neil, Subject: Titan IIIB, Contract AF 04(695)-730, Evaluation of a V. E. Project to Determine the Effect on System Reliability of Decreasing Engine Acceptance Testing
(d) Report #9947-IR-TE-37, dtd 7-22-65, Subject: Titan II Engine Reliability Risk Versus Test Duration, Contract AF 04(607)-9947

ENCLOSURE:
(1) Preliminary Summary of NERVA Full Flow Engine Component Failure Modes and Methods of Detection

In response to Reference (b), additional Reliability input to Trade Study #1001 is provided. A review of acceptance test criteria was conducted on the man-rated Apollo Service Propulsion System (SPS) engine. Components (valves, injector, chamber and actuators) of this engine underwent individual development, qualification and acceptance testing. The injector, for example, (after development and qualification tests) is hot-fired on a workhorse ablative thrust chamber ($\approx$300 seconds) as a test to determine if the pattern causes any chamber streaking. It is subsequently hot-fired on an uncooled steel chamber ($\approx$5 tests of 5 seconds each) to determine its performance (Isp). The injector is then put on an engine which is hot-fired as an engine acceptance test. This engine, however, has a workhorse thrust chamber and bipropellant valve. After the engine acceptance test, the engine is disassembled, decontaminated and reassembled, using a new (never fired on an engine) thrust chamber and bipropellant valve. During this reassembly process, rigorous inspection and QC coverage is provided. The deliverable engine is also leak and functionally checked before customer acceptance. The first hot-firing test of the thrust chamber and bipropellant valve will be during subsequent flight. Due to the design of the SPS engine, a full duration hot-firing acceptance test on the complete deliverable engine could considerably degrade the system reliability.

3.114

The Titan family of engines (Titan II, III, and Gemini), ran full duration hot-firing acceptance tests until it was shown, References (c) and (d), that some hot-firing acceptance tests could be eliminated or truncated without endangering reliability. This applied to both the component and complete engine level.

A preliminary Failure Mode Analysis (FMA) was conducted on the NERVA Engine non-nuclear system to determine what failures could occur and also how they could be detected. Enclosure (1) summarizes the results. A total of 34 failure modes was analyzed with the results that all but one of the failure modes could be detected on the component acceptance test level or by functional, leak and continuity checks on the complete engine level. Based upon previous engine programs, the nuclear engine design concept and the results of the FMAs conducted to date, this analysis indicates that from a reliability standpoint for the non-nuclear subsystem, hot-firing acceptance testing of the complete system is unnecessary and probably undesirable. Therefore maximum effort should be placed on component and subsystem testing and verification and perform a minimum number of activities at the engine assembly level. Reliability recommends, as per Reference (a), that performance of continuity, functional, and leak checks as a total engine acceptance test procedure. If power tests are essential for performance determination, then Reliability prefers the first ranked plan below in addition to the functional, continuity and leak checks.

Rank	Description
1.	Conduct low-power cold flow to pressure loop closure. Poison wire reinsertion not required.
2.	Conduct powered cold flow test to loop closure. Poison wire reinsertion not required.
3.	Conduct low-power cold flow to pressure loop closure only. Remove nozzle to reinsert poison wires for shipment.
4.	Conduct powered cold flow tests to a level where temperature and pressure loops are closed. Remove nozzle to reinsert poison wires for shipment.

As the NERVA Engine design becomes more and more definitive, additional reliability input will be presented. The finalized engine will be analyzed on a component-by-component basis. This detailed component FMA could be used to determine the effect of acceptance testing upon reliability.

Currently in process of preparation for the full flow NERVA Engine are detailed Failure Mode Effects and Criticality Analyses (FMECA). This analysis may reveal additional modes which are not detectable by means of functional type testing only. It is planned to request a similar analysis from WANL. The schedule for this task will be discussed in a coordination meeting planned for 13 November 1969.

CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE

for C. T. Lang
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

3.115

PRELIMINARY SUMMARY OF NERVA FULL FLOW ENGINE COMPONENT FAILURE MODES AND METHODS OF DETECTION

Component	Mode of Failure	Type of Test Required to Detect
A. VALVES		
PSOV, PDKV, BBV, BCV, TNV, TBV, SSCV, SSBV, CSKV, CSGV and TDKV SYKV	1. Failure to open	Functional
	2. Failure to close	Functional
	3. Fail in place	Functional
	4. Premature opening	Functional
	5. Premature closing	Functional
	6. Slow closing	Functional
	7. Fast opening	Functional
	8. Fast closing	Functional
	9. Slow opening	Functional
	10. Fail in position	Functional
	11. Internal leak	Leak check
	12. External leak	Leak check
	13. Reverse leakage	Leak check
	14. Excessive pressure drop	Flow check
B. LINES		
PDL, PIL, TIL, TDL, CSL, SSCL, SCBL SSGL	1. External leak	Leak check
	2. Excessive resistance or pressure drop	Flow check
C. TPA		
	1. Improper performance	TPA acceptance test
	2. Fail to start	Engine acceptance test
D. NOZZLE ASS'Y & SKIRT EXTENSION		
	1. External coolant leak	Leak check
	2. External hot gas leak	Leak check
	3. Internal coolant leak	Leak check
	4. Excessive pressure drop	Flow check
E. PRESSURE VESSEL & CLOSURE		
	1. External coolant leak	Leak check
	2. Coolant leakage to hot gas	Leak check

PRELIMINARY SUMMARY OF NERVA FULL FLOW ENGINE COMPONENT FAILURE MODES AND METHODS OF DETECTION (cont.)

Component	Mode of Failure	Type of Test Required to Detect
F. DESTRUCT SYSTEM		
	1. Fail to activate	Continuity Check
G. INSTRUMENTATION & CONTROLS		
	1. Open circuit	Continuity check
	2. Short circuit	Insulation and resistance
	3. Loss of resistance	Dielectric test
H. GIMBAL ASS'Y		
	1. Excessive torque	Torque check
	2. Fail to attain gimbal angle	Functional check
I. ACTUATORS		
Valves, Gimbal and Control Drums	1. Fail to respond to input command	Functional
	2. Slow response	Functional
	3. Fast response	Functional
	4. Improper response	Functional

2, 11 7

THE CAUSAL VARIABL... APPROACH IS ILLUSTRATED IN

MEMORANDUM

TO: P. P. Ventura

DATE: 18 December 1969
7850:M0378

FROM: E. B. Cleveland

SUBJECT: Reliability Review of Trade Study S-054-006, Diluent and Bolt Coolant Flow for NERVA Hot-Bleed Engine

COPIES TO: W. M. Bryan, D. Buden, A. D. Cornell, D. S. Duncan, W. E. Durkee, R. B. Glasscock, B. Mandell, J. H. Ramsthaler, E. A. Sheridan, W. E. Stephens, E. J. West, Section 7850 Personnel
NTO: W. H. Bushnell

REFERENCE: (a) Memo 7010:173, R. V. Evleth to Distribution, dated 1 Dec. 69, Subject: Review of Diluent and Bolt Coolant Flows, Data Item S-054-006

The subject trade study report, dated 1 December 1969, was reviewed as requested by Reference (a) with respect to the reliability conclusion and found to be in agreement with the supporting reliability analysis. A clerical error does appear in page 5, line 10. It should read: "...in Concept "A" than in Concept "C" ..."; the A and C having been interchanged.

E B Cleveland
E. B. Cleveland
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

3.1.5

MEMORANDUM

To:	W. E. Stephens	Date: 19 December 1969 7850:0393M
From:	J. H. Ramsthaler	
Subject:	System Level Failure Mode, Effects, and Criticality Analysis (FMECA)	
Copies To:	D. Buden, A. D. Cornell, W. E. Durkee, R. B. Glasscock, C. K. Leeper, B. Mandell, I. L. Odgers, E. A. Sheridan, File	
Reference:	(a) Memo J. H. Ramsthaler to C. K. Leeper dtd 10 December 1969, subj: "Component Failure Mode Analysis"	
Enclosure: (Addressee Only)	(1) Failure Mode Effects and Criticality Analysis	

In accordance with Reference (a), Enclosure (1) presents the initial iteration of the system level FMECAs for the NERVA reference engine (excluding the I&C and Nuclear Subsystems). In many areas, the engine or subsystem effect of a given failure mode is presently unknown. Computer malfunction runs on the NETAP or TAF programs will be made in some cases to determine these effects. In addition, assistance is requested from your section to work with the reliability analysts in upgrading this analysis.

W. M. Bryan /for
J. H. Ramsthaler, Manager
Reliability and Safety Analysis Section
NRO Systems Department

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Bryan 12/23/69
CLASSIFYING OFFICER DATE

3.11

[redacted]

STATUS REPORT PREPARED FOR

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

4.0 RELIABILITY METHODS

M E M O R A N D U M

To: W. M. Bryan

Date: 24 November 1969
7850:M0342

From: A. J. Mihanovich

Subject: Status - R-106 Efforts

Copies To: J. W. Brewer, J. S. Goddard, J. H. Ramsthaler, E. J. West, File

Reference: (a) AGC Report, W. A. Coleal to R. J. Squires dtd 22 November 1966, subj: "NERVA Reliability Study"

Enclosure: (1) General Comments - R-106
(2) Proposed Approach
(3) Considerations Related to Test Program Planning

The purpose of this memorandum is to briefly review the activities performed to date with reference to the development of Data Item R-106, Reliability Test and Evaluation Plan, list some potential problems, and to suggest possible approaches toward completing this data item.

A treatise on general reliability evaluation was presented in Reference (a). In addition, some general approaches were suggested for some of the components. As such, Reference (a) provides valuable background toward the problems of reliability assessment as applied to the NERVA development program, including some insight to the types of tests normally conducted on components during development programs.

Based on a review of Reference (a) and the requirements of R-106, Enclosure (1) has been prepared. This enclosure briefly summarizes some of the general comments pertinent to R-106 that are apparent at this time. It is clearly incomplete at this time, since the numbers of assumptions required, and problems identified, will increase as more efforts are expended on the R-106 task.

In Enclosure (2) is presented a brief outline of the type of approach which should be considered to complete the R-106 data item. The tasks presented in Enclosure (2) are sketchy at this point, may omit some important steps, and may be chronologically out of proper sequence; however, it is hoped that they would serve to stimulate comments and discussion on means for accomplishing this task.

Omitted from Enclosure (2) are the efforts required to improve the technical methodology of reliability assessment and the efforts required to resolve some of the technical problems presented in Enclosure (1). It is understood that these methods improvement efforts should be undertaken concurrently with the tasks presented in Enclosure (2).

Enclosure (3) contains a philosophical discussion of the overall reliability assessment problem, as prepared by J. W. Brewer.

A. J. Mihanovich
A. J. Mihanovich
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations 4.1

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Bryan 11/24
CLASSIFYING OFFICER DATE

GENERAL COMMENTS - R-106

A. ASSUMPTIONS

1. No testing will be conducted for reliability assessment purposes only. All testing should be designed to produce information required by and useful to the designer. (Implies that, in many cases, the designer must be educated as to what information he really needs).

2. The basic item which will delineate what numerical reliability values will be required is the Reliability Prediction Math Model. Not all of the values required for input to the model will be generated as a result of testing during the NERVA program, since in some cases it will not be feasible or possible to do sufficient testing to generate useful reliability data. (Possible examples -- pressure vessel, structures). In these cases, reliability values based on analytical analyses or possibly historical data will be utilized.

3. The same simplifying assumptions made in the development of the prediction model will also apply to the assessment model (e.g., independence, etc.)

B. GENERAL TESTING PROBLEMS

1. What type of design information do designers normally require from testing? This question holds for all parts/components/subsystems/systems.

2. At what level of testing (part, component, etc.) is reliability assessment really feasible? That is, at what level and what type of tests produce useful data in terms of realistic imposed environments, etc.

3. What type of tests are normally conducted on the various parts/components, etc? (Including what type of test equipment.)

4. Major Problem (at present) - Scope of R-106 as indicated in Form 9 (Data Item description)

4.2

C. TECHNICAL PROBLEMS

1. In analytical stress/strength analyses, stress distributions are derived by analyses of stress equations. During testing the stress distribution often changes as a function of thrust time. How is this considered for reliability assessment using stress/strength technique?

2. If results of engine tests are used and reliability assessment considers such engine parameters as Isp, how is this accomplished, since Isp is a continuous variable as a function of time? ($e^{-\lambda t}$)?

3. Some components are subject to changing failure rates due to deterioration/degradation. The technical reliability problems associated with this phenomenom have not to date been thoroughly explored.

4. Common externally and internally induced environments often affect failure modes from several components. These effects could pose difficult reliability assessment problems.

PROPOSED APPROACH

	Task	Responsibility
1.	Perform a detailed component Failure Mode and Effects Analysis including: a. Environmental conditions pertinent to each mode. b. Prediction of probability of occurrence of each mode (based on historical or analytical results).	Reliability
2.	Review materials testing requirements as developed by the Materials Department.	Reliability
3.	Review types and numbers of tests normally performed on each component/subsystem to provide design data.	Reliability/Design
4.	Review test equipment available for various component tests.	Reliability/Design
5.	Detail the design requirements for each component/subsystem.	Design
6.	Develop preliminary reliability assessment plan to suit requirements of the reliability math models.	Reliability
7.	Compile all preliminary component/subsystem test plans developed to date by Design.	Reliability
8.	Compare assessment requirements with potential data available from Item 7.	Reliability
9.	Suggest changes in the test program necessary to satisfy the assessment requirements. Coordinate with Design.	Reliability
10.	Publish final Reliability Test and Evaluation Plan.	Reliability

CONSIDERATIONS RELATED TO TEST PROGRAM PLANNING

I. TERMINOLOGY

This communication describes criteria which might be used in making decisions when planning Reliability tests.

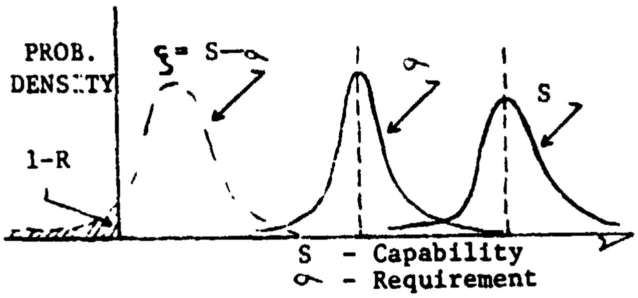


Figure 1 - The "Causal Variable" Formalism

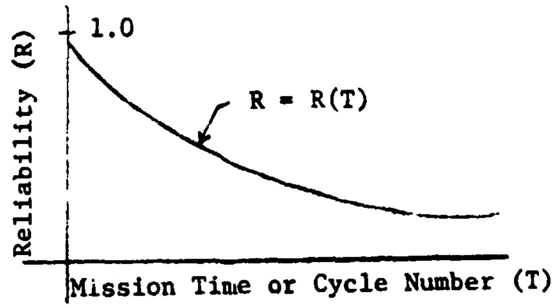


Figure 2 - The "Temporal-Phenomological" Formalism

It will be necessary to review standard terminology and, in the process, introduce several new terms in order to express the author's views. New terms will be designated by quotation marks.

There are at least two ways to formalize Reliability studies: (1) the "Temporal - Phenomological" model, and (2) the "causal variable" model.

In the "Temporal - Phenomological" approach, the analyst assumes:

$$R = R(T) \qquad 1$$

where T is either the mission time or cycle number, whichever is appropriate. The functional relation may then be assumed to have some standard form such as the Weibull cumulative distribution:

$$R = e^{-(\theta T)^b} \qquad 2$$

For many physical components, it is assumed that b = 1.0 so that equation 2 reduces to the familiar exponential distribution. The failure rates, θ, for many components can be found in standard data books such as FARADA.

In the causal "Variable Approach," the reliability is assumed to be the cumulative probability associated with some basic random variable, ξ $\dot{\mathfrak{z}}$, i.e.:

$$R = \text{PROB}\ (\xi > 0) \qquad 3$$

$$= F(o) \qquad 4$$

4.5

The analyst must then select a functional form for either F or its probability density

$$f = \frac{dF}{d\xi} \qquad 5$$

The causal variable approach is illustrated in Figure 1. Examples of the use of this approach are: (1) the stress - strength formalism for mechanical members and other so called "physics of failure theories;" in the theory, $\xi = S - \sigma$ (capability minus requirement) as shown in Figure; and (2) clearance failure theory (e.g., turbine blade and housing clearance) wherein ξ = clearance.

Testing based on the temporal - phenomological formalism will be referred to as "life testing." It is the purpose of this report to present criteria which will help the Reliability engineer select one form of testing over the other.

It will be assumed that Reliability may be resolved as follows:

R_S = Structural Reliability

R_P = Performance 6

As pointed by RAABE, R_P is the conditional probability that a system performs according to specification given that the system components maintain their structural characteristics. Structural Reliability will receive the main emphasis in the discussion.

In the following discussion, emphasis will be placed on two competing considerations:

a. Cost of testing

b. Accuracy of the experimental

Performance Reliability fits quite nicely into the causal variable formalism.

II. ADVANTAGES AND DISADVANTAGES OF CAUSAL-VARIABLE TESTING

It is clear that only the causal variable formalism can be applied to some components. For instance, mechanical components subject to large static loads only once during the mission. Most often, however, the analyst will have a choice of formalisms to use in his modeling and testing.

4.6

Often, the designer himself will be very interested in one of the random variables σ and/or S. The designer's testing needs might then conform with those of the Reliability Engineer. Before requesting tests, the Reliability should consider that the designer's experience and capabilities could be enhanced by causal variable testing.

Causal variable testing can offer great savings in test costs. Requirement statistics, for instance, can be obtained using non-destructive testing. After the analyst has selected F or f, appropriate statistics can often be obtained with a high degree of confidence after five or ten tests.

Another important consideration for the Reliability Analyst is the type of historical data which is available. If capability-requirement data is available, the Reliability Engineer may have greater confidence (in the non-statistical sense) in the data obtained in the testing program.

It would appear that the greatest disadvantage associated with the causal variable approach relates to questions of accuracy. Two major sources of inaccuracy are:

a. Requirement-capability relations must be defined for each failure mode; omission of a single failure mode in testing could completely invalidate an otherwise perfect Reliability estimate and assessment.

b. The definition of the capability variable, S, is a difficult task; this statement is especially true for mechanical members for which failure mechanisms are poorly understood and cannot be related to standard, simplified material tests.

These are, of course, the usual inaccuracies associated with a poor choice of the probability functions F or f.

III. <u>ADVANTAGES AND DISADVANTAGES OF LIFE TESTING</u>

Life testing has the significant advantage of possibly providing the more accurate Reliability assessment. Accuracy of life testing results is not seriously affected by an incomplete failure mode analysis.

Many types of hardware (e.g., ball and roller bearings, electric circuit components) have been modeled in this phenomological way and much historical data exists for these components. For some components, life data is easier to obtain than capability-requirement data (e.g.. rolling bearings and electrical components).

It is possible, with life testing, to substitute histogram analysis for estimating statistical distribution parameters and thereby eliminate errors introduced by the assumption of an inappropriate form of probability functions. Histogram analysis, however, usually requires a much larger number of tests.

The usefulness of temporal-phenomological or life testing suffers from the facts that:

a. Life testing sheds little light on those aspects of design not directly related to Reliability.

b. The number and length of life tests can lead to large testing costs.

There are several distinct categories of life testing that should be delineated. Two basic types of testing are:

a. Attribute Testing

b. Testing to Failure

In atrribute testing, parts and/or systems are tested for a specified time or number of cycles. Reliabilities and confiderce limits are then deducted from the survival ratio. Attribute testing offers the advantage of providing the Reliability Engineer with a straight-forward means of calculating confidence parameters. As is well known, attribute testing requires an extremely large number of tests in order to provide sufficiently narrow confidence limits. Thus, the analyst must weigh the advantage of knowledge of confidence parameters against testing costs when considering attribute testing.

Testing to failure tests can be broken down into two sub-categories:

B - 1) Histogram Analysis

B - 2) Statistics estimation for assumed probability functions

4, 5

Obviously, histogram analysis provides the more accurate means of testing because there is no need for assuming a form for probability functions. If the analyst decides that testing costs for histogram analysis would be too high, he might decide on B-2) life testing.

IV. SUMMARY AND CONCLUSIONS

There are basic types of testing: "causal variable" and life testing. The Reliability Engineer may often have to choose between the two types of formalism when developing Reliability models and when designing tests. When selecting a formalism, the analyst might consult the following checklist:

a. To which formalism is historical data related?

b. Are other members of the design team planning tests which might be used as "causal variable" tests?

c. Will "causal variable" testing enhance the capability of designers?

d. Are the distribution functions, which must be assumed in the causal variable formalisms, sufficiently accurate approximations of the true distributions?

e. Is the failure mode analysis, which is especially crucial to causal variable testing, sufficiently complete?

f. If life testing is selected, are confidence parameters required?

g. What number of life tests must be performed and what are the lengths of the tests? What are the associated costs?

h. Will histogram analysis of life tests result in sufficiently low test costs so that this type of test analysis may be used in place of statistics analysis for assumed distributions?

The answers to the above questions will hopefully provide the Reliability Analyst with a rational basis for design of tests.

4/1

[illegible] RELATED TO TEST PROGRAM PLANNING

I TERMINOLOGY

THIS COMMUNICATION DESCRIBES CRITERIA WHICH MIGHT BE USED IN MAKING DECISIONS WHEN PLANNING RELIABILITY TESTS.

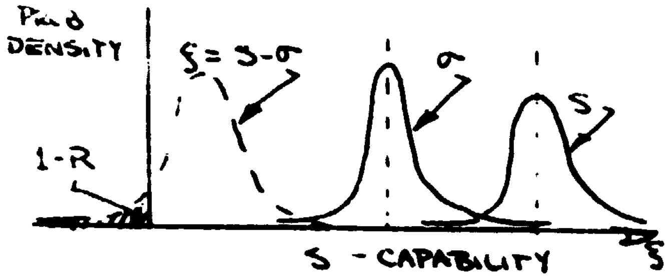


FIG. 1 THE "CAUSAL VARIABLE" FORMALISM

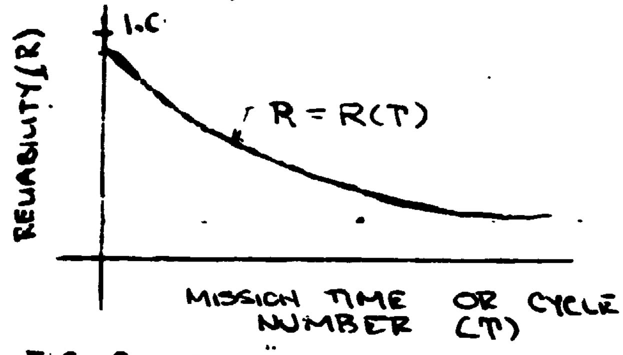


FIG. 2 THE "TEMPORAL-PHENOMOLOGICAL" FORMALISM

IT WILL BE NECESSARY TO REVIEW STANDARD TERMINOLOGY AND, IN THE PROCESS, INTRODUCE SEVERAL NEW TERMS IN ORDER TO EXPRESS THE AUTHORS VIEWS. NEW TERMS WILL BE DESIGNATED BY QUOTATION MARKS.

THERE ARE AT LEAST TWO WAYS TO FORMALIZE RELIABILITY STUDIES: 1) THE "TEMPORAL-PHENOMOLOGICAL" MODEL; AND 2) THE "CAUSAL VARIABLE" MODEL.

IN THE "TEMPORAL-PHENOMOLOGICAL" APPROACH THE ANALYST ASSUMES

$$R = R(T)$$

WHERE T IS EITHER THE MISSION TIME OR CYCLE NUMBER, WHICHEVER IS APPROPRIATE. THE FUNCTIONAL RELATION MAY THEN BE ASSUMED TO HAVE SOME STANDARD FORM SUCH AS THE WEIBULL CUMULATIVE DISTRIBUTION

$$R = e^{-(\theta T)^b} \quad 2$$

FOR MANY PHYSICAL COMPONENTS, IT IS ASSUMED THAT $b = 1.0$ SO THAT EQN. 2 REDUCES TO THE FAMILIAR EXPONENTIAL DISTRIBUTION. THE FAILURE RATES, θ, FOR MANY COMPONENTS CAN BE FOUND IN STANDARD DATA BOOKS SUCH AS FARADA.

IN THE "CAUSAL VARIABLE APPROACH", THE RELIABILITY IS ASSUMED TO BE THE CUMULATIVE PROBABILITY ASSOCIATED WITH SOME BASIC RANDOM VARIABLE, ξ; i.e.

$$R = \text{PROB}\,(\xi > 0) \quad 3$$

$$= F(0) \quad 4$$

THE ANALYSIST MUST THEN SELECT A FUNCTIONAL FORM FOR EITHER F OR ITS PROBABILITY DENSITY

$$f = \frac{dF}{d\xi} \quad 5$$

4.10

THE CAUSAL VARIABLE [illegible] IS ILLU[illegible] ..
FIG. 1. EXAMPLES OF THE USE OF THIS APPROACH ARE: 1) THE STRESS - STRENGTH FORMALISM, FOR MECHANICAL MEMBERS AND OTHER SO CALLED "PHYSICS OF FAILURE THEORIES; IN THE THEORY, $\xi = S - T$ (CAPABILITY MINUS REQUIREMENT) AS SHOWN IN FIGURE 1 2) CLEARANCE FAILURE THEORY (e.g. TURBINE BLADE AND HOUSING CLEARANCE) WHEREIN ξ = CLEARANCE.

TESTING BASED ON THE TEMPORAL-PHENOMOLOGICAL FORMALISM WILL BE REFERRED TO AS "LIFE TESTING". TESTING BASED ON THE CAUSAL VARIABLE FORMALISM WILL BE REFERRED TO AS "CAUSAL VARIABLE TESTING". IT IS THE PURPOSE OF THIS REPORT TO PRESENT CRITERIA WHICH WILL HELP THE RELIABILITY ENGINEER ~~THE~~ SELECT ONE FORM OF TESTING OVER THE OTHER.

IT WILL BE ASSUMED THAT RELIABILITY MAY BE RESOLVED AS FOLLOWS

$$R = R_s R_p \qquad (6)$$

R_s = STRUCTURAL RELIABILITY
R_p = PERFORMANCE "

AS POINTED BY RAABE, R_p IS THE CONDITIONAL PROBABILITY THAT A SYSTEM PERFORMS ACCORDING TO SPECIFICATION GIVEN THAT THE SYSTEM ~~MAINTAINS~~ COMPONENTS MAINTAIN THEIR STRUCTURAL ~~AND FUNCTIONAL~~ CHARACTERISTICS. STRUCTURAL RELIABILITY WILL RECIEVE THE MAIN EMPHASIS IN THE DISCUSSION. IN THE FOLLOWING DISCUSSION, EMPHASIS WILL BE PLACED ON TWO COMPETING CONSIDERATIONS:

A) COST OF TESTING
B) ACCURACY OF THE EXPERIMENTAL RELIABILITY DETERMINATION.

PERFORMANCE RELIABILITY FITS QUITE NICELY INTO THE CAUSAL VARIABLE FORMALISM

II ADVANTAGES AND DISADVANTAGES OF CAUSAL-VARIABLE TESTING

IT IS CLEAR THAT ONLY THE CAUSAL VARIABLE FORMALISM CAN BE APPLIED TO SOME COMPONENTS. FOR INSTANCE, MECHANICAL COMPONENTS SUBJECT TO LARGE STATIC LOADS ONLY ONCE DURING THE MISSION. MOST OFTEN HOWEVER, THE ANALYST WILL HAVE A CHOICE OF FORMALISMS TO USE IN HIS MODELING AND TESTING.

OFTEN, THE DESIGNER HIMSELF WILL BE VERY INTERESTED IN ONE OF THE RANDOM VARIABLES σ AND/OR S. THE DESIGNER'S TESTING NEEDS MIGHT THEN CONFORM WITH THOSE OF THE RELIABILITY ENGINEER. BEFORE REQUESTING TESTS, THE RELIABILITY SHOULD CONSIDER THAT THE DESIGNERS EXPERIANCE AND CAPABILITIES ~~WILL BE~~ COULD BE INHANCED BY CAUSAL VARIABLE TESTING. 4.1

CAUSAL VARIABLE TESTING CAN OFFER GREAT SAVINGS IN TEST COSTS. REQUIREMENT STATISTICS, FOR INSTANCE CAN BE OBTAINED USING NON-DISTRUCTIVE TESTING. AFTER THE ANALYST HAS SELECTED F OR f

APPROPRIATE STATISTICS CAN OFTEN BE OBTAINED WITH A HIGH DEGREE OF CONFIDENCE AFTER FIVE OR TEN TESTS.

ANOTHER IMPORTANT CONSIDERATION FOR THE RELIABILITY ANALYST IS THE TYPE OF HISTORICAL DATA WHICH AVAILABLE. IF CAPABILITY - REQUIREMENT DATA IS AVAILABLE, THE RELIABILITY ENGINEER MAY HAVE GREATER CONFIDENCE (IN THE NON-STATISTICAL SENSE) IN THE DATA OBTAINED IN THE TESTING PROGRAM.

IT WOULD APPEAR THAT THE GREATEST DISADVANTAGE ASSOCIATED WITH THE CAUSAL VARIABLE APPROACH RELATE TO QUESTIONS OF ACCURACY. TWO MAJOR SOURCES OF INACCURACY ARE:

1) REQUIREMENT - CAPABILITY RELATIONS MUST BE DEFINED FOR EACH FAILURE MODE; OMMISSION OF A SINGLE FAILURE MODE IN TESTING COULD COMPLETELY INVALIDATE AN OTHERWISE PERFECT RELIABILITY ESTIMATE AND ASSESMENT.

2) THE DEFINITION OF THE CAPABILITY VARIABLE, S, IS A DIFFICULT TASK; THIS STATEMENT IS ESPECIALLY TRUE FOR MECHANICAL MEMBERS FOR WHICH FAILURE MECHANISMS ARE POORLY UNDERSTOOD AND CANNOT BE RELATED TO STANDARD, SIMPLIFIED MATERIAL TESTS.

THERE ARE OF COURSE, THE USUAL INACCURIES ASSOCIATED WITH A POOR CHOICE OF THE PROBABILITY FUNCTIONS F OR f.

II ADVANTAGES AND DISADVANTAGES OF LIFE TESTING

LIFE TESTING HAS THE SIGNIFICANT ADVANTAGE OF POSSIBLY PROVIDING THE MORE ACCURATE RELIABILITY ASSESMENT. ACCURACY OF LIFE TESTING RESULTS IS NOT SERIOUSLY AFFECTED BY AN INCOMPLETE FAILURE MODE ANALYSIS.

MANY TYPES OF HARDWARE (e.g. BALL AND ROLLER BEARINGS, ELECTRIC CIRCUIT COMPONENTS) HAVE BEEN MODELED IN THIS PHENOMOLOGICAL WAY AND MUCH HISTORICAL DATA EXISTS FOR THESE COMPONENTS. FOR SOME COMPONENTS, LIFE DATA IS EASIER TO OBTAIN THAN CAPABILITY - REQUIREMENT DATA (e.g. ROLLING BEARINGS AND ELECTRICAL COMPONENTS). 4.12

IT IS POSSIBLE, WITH LIFE TESTING, TO SUBSTITUTE HISTOGRAM ANALYSIS FOR ~~STANDARD~~ ESTIMATING

STATISTICAL DISTRIBUTION ~~ANALYSES~~ AND THUS ELIMINATE ERRORS INTRODUCED BY THE ASSUMPTION OF AN INAPPROPRIATE FORM OF ~~A~~ PROBABILITY FUNCTIONS. HISTOGRAM ANALYSIS, HOWEVER, USUALLY REQUIRES A ~~GOOD~~ MUCH LARGER NUMBER OF TESTS. THE ~~TEMPORAL~~ PHENOMENOLOGICAL OR LIFE TESTING SUFFERS FROM THE FACTS THAT:

1) LIFE TESTING SHEDS LITTLE LIGHT ON THOSE ASPECTS OF DESIGN NOT DIRECTLY RELATED TO RELIABILITY.
2) THE NUMBER AND LENGTH OF LIFE TESTS CAN LEAD TO LARGE TESTING COSTS.

THERE ARE SEVERAL DISTINCT CATEGORIES OF LIFE TESTING THAT SHOULD BE DELINEATED. TWO BASIC TYPES OF TESTING ARE

A) ATTRIBUTE TESTING
B) TESTING TO FAILURE

IN <u>ATTRIBUTE TESTING</u>, PARTS AND/OR SYSTEMS ARE TESTED FOR A SPECIFIED TIME OR NUMBER OF CYCLES. RELIABILITIES AND CONFIDENCE LIMITS ARE THEN DEDUCED FROM THE SURVIVAL RATIO. ATTRIBUTE TESTING OFFERS THE ADVANTAGE OF PROVIDING THE RELIABILITY ENGINEER WITH A STRAIGHT FORWARD MEANS OF CALCULATING CONFIDENCE PARAMETERS. AS IS WELL KNOWN, ATTRIBUTE TESTING REQUIRES AN EXTREMELY LARGE NUMBER OF TESTS IN ORDER PROVIDE SUFFICIENTLY NARROW CONFIDENCE LIMITS. THUS, THE ANALYST MUST WEIGH THE ANDVANTAGE OF KNOWLEDGE OF CONFIDENCE PARAMETERS AGAINST ~~TESTS~~ TESTING COSTS WHEN CONSIDERING ATTRIBUTE TESTING.

<u>TESTING TO FAILURE</u> TESTS CAN BE BROKEN DOWN INTO TWO SUB-CATEGORIES

B-1) HISTOGRAM ANALYSIS
B-2) STATISTICS ESTIMATION FOR ASSUMED PROBABILITY FUNCTIONS.

OBVIOUSLY, HISTOGRAM ANALYSIS PROVIDES THE MORE ACCURATE MEANS OF TESTING BECAUSE THERE IS NO NEED FOR ASSUMING A FORM FOR PROBABILITY FUNCTIONS. IF THE ANALYST DECIDES THAT TESTING COSTS FOR HISTOGRAM ANALYSIS WOULD BE TOO HIGH, HE MIGHT DECIDE ON B-2) LIFE TESTING.

III SUMMARY AND CONCLUSIONS

THERE ARE BASIC TYPES OF TESTING: "CAUSAL VARIABLE" AND LIFE TESTING. THE RELIABILITY ENGINEER MAY OFTEN HAVE TO CHOOSE BETWEEN THE TWO TYPES OF FORMALISM WHEN DEVELOPING RELIABILITY MODELS AND WHEN DESIGNING TESTS. WHEN SELECTING A FORMALISM, THE ANALYST MIGHT CONSULT THE

[redacted] Enclosure (

FOLLOWING CHECK LIST:

1) TO WHICH FORMALISM IS HISTORICAL DATA RELATED ?

2) ARE OTHER MEMBERS OF THE DESIGN TEAM PLANNING TESTS WHICH MIGHT BE USED AS "CAUSAL VARIABLE" TESTS ?

3) WILL "CAUSAL VARIABLE" TESTING ENHANCE THE CAPABILITY OF DESIGNERS ?

4) ARE THE DISTRIBUTION FUNCTIONS, WHICH MUST BE ASSUMED IN THE CAUSAL VARIABLE FORMALISMS, SUFFICIENTLY ACCURATE APPROXIMATIONS OF THE TRUE DISTRIBUTIONS ?

5) IS THE FAILURE MODE ANALYSIS, WHICH IS (ESPECIALLY) CRUCIAL TO CAUSAL VARIABLE TESTING, SUFFICIENTLY COMPLETE ?

6) IF LIFE TESTING IS SELECTED, ARE CONFIDENCE PARAMETERS ~~WHICH ARE MOST EASILY OBTAINED IN ATTRIBUTE TESTING,~~ REQUIRED ?

7) WHAT NUMBER OF LIFE TESTS MUST BE PERFORMED AND WHAT ARE THE LENGTHS OF THE TESTS ? WHAT ARE THE ASSOCIATED COSTS

8) WILL HISTOGRAM ANALYSIS OF LIFE TESTS ~~REQUIRE~~ IN SUFFICIENTLY LOW TEST COSTS SO THAT ~~MAKES~~ THIS TYPE OF TEST ANALYSIS MAY BE USED IN PLACE OF STATISTICS ANALYSIS FOR ASSUMED DISTRIBUTIONS ?

THE ANSWERS TO THE ABOVE QUESTIONS WILL HOPEFULLY ~~LEAD~~ PROVIDE THE RELIABILITY ANALYST WITH A RATIONAL BASIS FOR ~~THE~~ DESIGN OF TESTS.

MEMORANDUM

TO:	J. L. Watkins	DATE: 16 December 1969 7850:M0371
FROM:	E. B. Cleveland	
SUBJECT:	Example of Designing for Reliability	
COPIES TO:	W. M. Bryan, D. Buden, L. B. Claassen, R. B. Glasscock, J. M. Klacking, A. J. Mihanovich, J. H. Ramsthaler, E. A. Sheridan, L. A. Shurley, M. H. Smoot, F. C. Valls, E. J. West NTO: W. H. Bushnell	
ENCLOSURE:	(1) Designing for Reliability	

The discussion and example of Enclosure (1) is provided to illustrate the use of SNPO-C-1 requirements by the designer to ensure achieving the overall engine reliability.

It is assumed that the designer understands some of the fundamentals of statistics. The bibliography references should be studied to gain a complete understanding of the probabilistic design concept.

Reliability personnel are always available to assist the designer in applying these principles.

E. B. Cleveland

E. B. Cleveland
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Bryan 12/16/69
CLASSIFYING OFFICER DATE

4.15

DESIGNING FOR RELIABILITY

The NERVA engine must have a reliability of 0.995 at the 90% confidence level to meet the long-life and man-rating requirements. The only possible way this level of operational excellence can be achieved is by painstaking attention to every detail of engine design, manufacture and use.

This effort begins with the designer who must convert the engine requirements into a design. The engine design must have a very high apparent design reliability to allow for manufacturing and use degradation and still achieve the 0.995 engine operational reliability. This is discussed in SNPO-C-1, Section 5. Since there are approximately 30 major engine components, it follows that the components must have design reliabilities on the order of 0.999 and the parts 0.999,999.

The only method currently available to the designer to achieve and assess this degree of the perfection is the Failure Mode Analysis and Probabilistic Design. The Failure Mode Analysis, covered in NRP 301, provides the attention to detail necessary to find all possible modes of failure. Probabilistic Design is the quantitative technique to be applied to each possible failure mode to ensure that all parts will have acceptably low failure probabilities.

Probabilistic Design is based on the premise that we live in a probabilistic world where no parameter is single-valued but is distributed in a manner that can be closely approximated by statistical mathematics. The techniques to apply these mathematics to the design process have been developed and are adequately covered in the references listed in the attached bibliography.

Full utilization of the probabilistic approach depends on the complete statistical description of the environment, the design configuration and the properties of the materials and processes used. This data is not available for many of the NERVA engine parameters and materials; however, reasonable estimates can be made of the distributions. These estimates will then permit initiation of a design using the probabilistic approach. Later, the results can be refined by substitution of actual data into the analysis.

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The following approach is suggested for use by the designer for initial design verification and comparison of alternative concepts and presumes that a failure mode analysis has been completed.

a. Define the failure criterion and the method of stress analysis.

b. Define all known parameters in terms of a means and standard deviations.

c. Compute the unknown parameter using the allocated reliability.

d. Determine the margin of safety.

e. Repeat for all critical areas and failure modes of each concept and tabulate the results.

The reliability value that must be achieved for each possible component failure mode is the result of apportioning the 0.995 engine requirement to each subsystem, component and part. This is done by a math model which takes into account the working relationships and the degree of difficulty expected in achieving the individual reliabilities.

A typical apportioned reliability for the nozzle assembly is 0.9_3746, which is divided into 0.9_3891 for the nozzle, 0.9_403 for the skirt and 0.9_4515 for the skirt extension. These values must be further apportioned by the designer to individual parts and then to each failure mode.

For example, the nozzle may have 220 tubes with four failure modes each, and a support structure with three failure modes. If any one of these failures will result in mission failure then their reliabilities are a series relationship and a simple approach would be to apportion the 0.9_3891 nozzle reliability equally to each of the failure modes.

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Tube Failures	220 x 4	=	880
Structure Failure	1 x 3	=	3
			883
Skirt Failure Rate	$1-.9_3891$	=	$.0_3109$
Mode Failure Rate	$\frac{.0_3109}{883}$	=	$.0_612$
Mode Reliability	$1-.0_612$	=	$.9_688$

This indicates that for each area of the nozzle that can fail, the probability of not failing must be at least 0.9_688 including not only the strength-stress effects but also Q.C. considerations such as corrosion, handling damage and undetected flaws. Again, a simple first-cut approach might be to assume that half of the failures are from undefined Q.C. problems.

$$\text{Strength-Stress Reliability} \quad 1-\frac{.0_612}{2} = .9_740$$

The $.9_740$ value can now be considered as a target value to initially size the structure. Several iterative steps will, of course, be required to arrive at an optimum nozzle design.

The following example illustrates the above procedure. The permissable Δp across the u-tube for a range of radii, wall thickness and strengths is determined for a reliability of $.9_740$. The designer should also study SNPO-C-1 giving particular attention to Section 5 and the examples of Appendix IV. Ed Haugen's book, Part Two, Chapters 7-14, should be referred to for examples of common stress problems using the probabilistic approach.

4.18

BIBLIOGRAPHY

1. Haugen, E. B., "Probabilistic Approaches to Design," Wiley and Sons, 1968

2. Kececioglu, D., and Cormier, D., "Designing a Specified Reliability Directly into a Component," University of Arizona, a paper, 1964

3. NASA Specification SNPO-C-1, NERVA Program Structural Design Requirements, 1968

4. Aerojet Report 9600:M003, "A Practical Approach to Selecting Design Safety Factors Based on the Distribution of Stress and Strength," Volumes I and II, P. H. Raabe, 1968

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PROBLEM

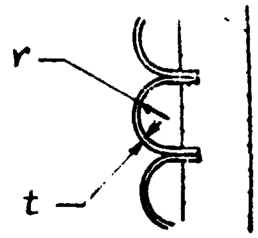
Determine the permissable pressure across th wall of u-tubes with outside radii of 0.177 and 0.284 and thicknesses of 0.012 to 0.038 in. for a mean wall temperature of 1000°R. The margin of safety must be positive and the apparent design reliability at least $0.9_{7}40$.

Step 1. Define the failure criteria and the method of stress analysis.

For this example consider the capability of the nozzle u-tube near the end of the nozzle to resist yielding during steady state engine operation.

$$f_{ty,\ hoop} = \frac{Pr}{t}$$

where P = ΔP across the wall
r = tube mean radius
t = tube wall thickness



u-tube section

Step 2. Define all parameters in terms of mean and standard deviation or coef. of variation. (A reasonable estimate of std. dev. is 1/3 of 10% of the mean or 1/3 of the specified one sided tolerance on the mean.)

Parameter (i)	Mean ($\bar{i}$)	Standard Deviation (σ_i)	Coef. of Var. (V_i)
Pressure, P, psid	(TBD)	$V_p \times \bar{P}$	.010
Outside Radius, r, in.	.177 and .284	$V_r \times \bar{r}$	.002
Wall Thickness, t, in.	.012 to .038	$V_t \times \bar{t}$	.048
Mat'l Strength, F_{ty}, psi, at 1000°R	24,800	1670	---

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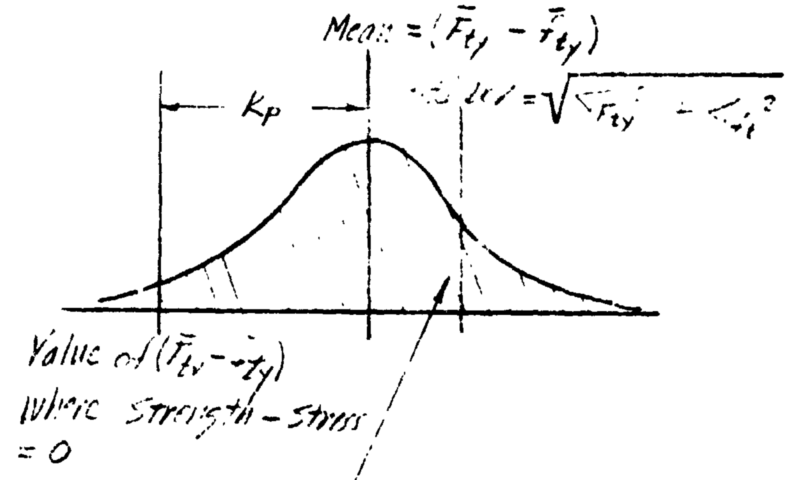
Step 3. Compute the unknown parameter.

The value of Kp is a measure of the number of standard deviations from the mean of the joint distribution of all values of strength greater than stress that will encompass .9740 of the area under the distribution curve as illustrated below.



$$Kp = \frac{\text{joint mean}}{\text{joint std dev.}} = \frac{\bar{F}_{ty} - \bar{f}_{ty}}{\sqrt{\sigma F_{ty}^2 + \sigma f_{ty}^2}}$$

Shaded area is the probability that any value of F_{ty} will be greater than any value of f_{ty}, i.e, the probability of success or (the reliability).

The values of $\bar{F}_{ty}$ and σF_{ty} are known and the value of $\bar{f}_{ty}$ and σf_{ty} (the stress mean and std. dev) can be determined from the expression $f_{ty} = Pr/t$ and the equation of the algebra of normal functions, Figure 1, by the method of partial derivatives, Figure 2 or by the Monte Carlo simulation technique.

Using the method of Partial Differentials, the mean and variance of stress are given by

$$\bar{f}_{ty} = \overline{Pr/t}$$

$$\sigma_{f_{ty}}^2 = \left(\frac{\partial f_{ty}}{\partial P}\sigma_P\right)^2 + \left(\frac{\partial f_{ty}}{\partial r}\sigma_r\right)^2 + \left(\frac{\partial f_{ty}}{\partial t}\sigma_t\right)^2$$

Since $\bar{F}_{ty}/\bar{P} = \bar{r}/\bar{t}$ and $\bar{F}_{ty}/\bar{r} = \bar{P}/t$ the partials reduce to

$$\frac{\partial f_{ty}}{\partial P} = \frac{r}{\bar{t}} = \frac{f_{ty}}{\bar{P}} \qquad \frac{\partial f_{ty}}{\partial t} = \frac{Pr}{\bar{t}^2} = \frac{f_{ty}}{\bar{t}}$$

$$\frac{\partial f_{ty}}{\partial r} = \frac{P}{\bar{t}} = \frac{f_{ty}}{\bar{r}}$$

Replacing the partials and dividing by f_{ty}^2

$$\left(\frac{\sigma_{f_{ty}}}{f_{ty}}\right)^2 = \left(\frac{\sigma_P}{\bar{P}}\right)^2 + \left(\frac{\sigma_r}{\bar{r}}\right)^2 + \left(\frac{\sigma_t}{\bar{t}}\right)^2$$

The standard deviation divided by the mean $(\sigma^i/\bar{i})$, is called the coefficient of variation usually expressed as V_i therefore $\bar{P}$, $\bar{r}$, and $\bar{t}$ terms can be replaced with V_p, V_r and V_t respectively.

$$\sigma_{f_{ty}}^2 = f_{ty}^2 \left(V_P^2 + V_r^2 + V_t^2\right)$$

Substituting this expression for σf_{ty}^2 in the expression for the Kp and solving for f_{ty}

$$K_P = \frac{\bar{F}_{ty} - \bar{f}_{ty}}{\sqrt{\sigma_{F_{ty}}^2 + f_{ty}^2\left(V_P^2 + V_r^2 + V_t^2\right)}}$$

which reduces to

$$\bar{f}_{ty}^2\left(1 - K_P^2\left(V_P^2 + V_r^2 + V_t^2\right)\right) + \left(-2\bar{F}_{ty}\right)\bar{f}_{ty} + \left(\bar{F}_{ty}^2 - K_P^2\sigma_{F_{ty}}^2\right) = 0$$

using the quadratic

$$\bar{f}_{ty} = \frac{\bar{F}_{ty} - \sqrt{\bar{F}_{ty}^2 - \left(1 - K_P^2\left(V_P^2 + V_r^2 + V_t^2\right)\right)\left(\bar{F}_{ty}^2 - K_P^2\sigma_{F_{ty}}^2\right)}}{\left(1 - K_P^2\left(V_P^2 + V_r^2 + V_t^2\right)\right)}$$

The appropriate value of K_p can be obtained from Figure 3. Since this is a function of average sample size, N, of the joint distribution of strength minus stress and the stress values are as yet undetermined, an initial value will have to be assumed and the final results corrected after the stress values are calculated.

The value of $\bar{P}$ can now be determined from

$$P \quad (f_{ty})(\bar{t})/\bar{r}$$

and the value of σp from $V_p^{\,2} = (\sigma p/\bar{P})^2$

$$\sigma p = V_p \bar{P}$$

Step 4. Determine the margin of safety (SNPO-C-1 requires a positive margin of safety regardless of the reliability value).

$$MS = \frac{SIL}{f} - 1, \text{ must be } \geq 0$$

where: $SIL = 0.85\,(F_{ty} - K_{F_{ty}}\,\sigma_{F_{ty}})$ SIL is Stress Intensity Limit based on nominal tensile yield strength F_{ty} and its variance $\sigma_{F_{ty}}$

and maximum allowable stress:

$$f = \bar{f}_{ty} + K_{f_{ty}}\,\sigma_{f_{ty}}$$

and: $K_{F_{ty}}$ & $K_{f_{ty}}$ = standard deviation multipliers which adjust the variance for confidence that a given sample size is able to predict the total population spread.

For this example assume that the material strength, variation $\sigma_{F_{ty}}$, is based on a sample of 15, the minimum allowed by TD 69-28. C-1 requires 95% confidence level: $\gamma = 0.95$, and (probability of 99%) $\alpha = 0.01$ and with sample size $n = 15$, the value of $K_t = 3.52$ using Figure 4.

Generally stress data is not available, and therefore are analytically derived. Since there is no sample size that can be associated with these derived values, it is generally assumed that the stress, f_{ty} and $\sigma_{f_{ty}}$, are from a very large sample size (infinite) therefore, Figure 5 is used at the 99% reliability $K_f = 2.33$. This corresponds to the 99% reliability used in the material strength calculation. The 95% confidence limit does not apply since the infinite population assumes absolute confidence.

$$MS = \frac{0.85\left(\bar{F}_{ty} - 3.52\,(\sigma F_{ty})\right)}{\bar{f}_{ty} + 2.33\,(\sigma f_{ty})} - 1$$

Step 5. Determine the reliability.

The reliability, R, will be the value from Figure 5 corresponding to the number of standard deviations, K_p, at sample size N. Since an infinite sample size is used with stress and a sample size of 15 is used with strength the average sample size is somewhere between 15 and ∞ and can be approximated by:

$$N + \frac{\left((\sigma_{F_{ty}})^2 + (\sigma_{f_{ty}})^2\right)^2}{\dfrac{\left((\sigma F_{ty})^2\right)^2}{N_{F_{ty}}} + \dfrac{\left((\sigma_{f_{ty}})^2\right)^2}{N_{f_{ty}}}}$$

A short GE Mark II Fortran program, ECLEVE 3, has been written for the numerical solution of this problem. The program is listed in Figure 6 and the output results of this sample problem are Figure 7. The input notations are as follows:

N	=	The number of mean wall temp. values (up to 50 sets of temp/strengths values can be entered. Only one set was used in this problem.)
TEMP	-	The mean wall temperature
FTY	-	The mean yield strength at TEMP

SIGFTY	- The std. dev. of FTY
OR (1) & (2)	- The tube outside radius, (the program is set up for two values)
FTYM	- The strength multiplier, $K_{F_{ty}}$ used to calculate SIL.
FTYN	- The strength sample size number (15 was used in this problem)
FM	- The stress multiplier, K_F used to calculate the max stress, f
RF	- The reliability factor K_p
VP, VR, VT	- The coefs of var. for pressure, radius and thickness

Step 6. Repeat for all critical areas and tabulate the results.

The computer solution presented does not yield a value for reliability. This is obtained from Figure 3 at the initial value used for K_p (6.85 in this problem) and the calculated value of average sample size EN. For this run the desired reliability of $0.9_7 40$ was obtained.

If a Component Failure Mode Analysis had been made to identify all nozzle failure modes, each mode would be analyzed using this approach. A summation of the results would then show that the design would be the required nozzle reliability of $0.9_3 891$.

METHOD FOR DETERMINING THE JOINT MEAN AND STANDARD DEVIATION OF TWO NORMALLY DISTRIBUTED VARIABLES

Operation	Joint Mean	Joint Std. Deviation
Addition	$\hat{x}_{a+b} = \bar{x}_a + \bar{x}_b$	$\hat{s}_{a+b} = (\bar{s}_a{}^2 + \bar{s}_b{}^2 + 2r\,\bar{s}_a\,\bar{s}_b)^{1/2}$
Subtraction	$\hat{x}_{a-b} = \bar{x}_a - \bar{x}_b$	$\hat{s}_{a-b} = (\bar{s}_a{}^2 + \bar{s}_b{}^2 - 2r\,\bar{s}_a\,\bar{s}_b)^{1/2}$
Multiplication	$\hat{x}_{ab} = \bar{x}_a\,\bar{x}_b$	$\hat{s}_{ab} = \bar{x}_a\bar{x}_y\left(\left(\frac{(\bar{s}_a)^2}{(\bar{x}_a)^2} + \frac{(\bar{s}_b)^2}{(\bar{x}_b)^2} + \frac{(\bar{s}_a)^2(\bar{s}_b)^2}{(\bar{x}_a)^2(\bar{x}_b)^2}\right) - (1-r^2)\right)^{1/2}$
Division	$\hat{x}_{a/b} = \bar{x}_a/\bar{x}_b$	$\hat{s}_{a/b} = \frac{(\bar{x}_a)^2}{(\bar{x}_b)^2}\left(\frac{(\bar{s}_a)^2}{(\bar{x}_a)^2} + \frac{(\bar{s}_b)^2}{(\bar{x}_b)^2} - 2r\frac{(\bar{s}_a)(\bar{s}_b)}{(\bar{x}_a)(\bar{x}_b)}\right)^{1/2}$

Where $\hat{x}$ = mean of j.d.

$\hat{s}$ = standard deviation of j.d.

$\bar{x}$ = mean of a sample

$\bar{s}$ = standard deviation of a sample

r = correlation coefficient (= o if functions are independent, +1 if perfectly correlated, -1 if negatively correlated)

a,b = subscripts denoting sample distributions

For more complex relationships use the method of partial derivatives.

PARTIAL DERIVATIVE METHOD FOR OBTAINING THE JOINT MEAN AND STANDARD DEVIATION OF TWO OR MORE NORMALLY DISTRIBUTED VARIABLES

This method can be used to obtain the approximate joint distribution of two or more functions and is recommended for those expressions that are more complex than the addition, subtraction, multiplication or division of two variables.

Operation	Joint Mean	Joint Standard Deviation
Any differentiable expression*	Use mean values in the expression.	$\hat{s}_y^2 = \sum_{i=1}^{1} \left(\frac{\partial y}{\partial x_i}\right)^2 \bar{s}_{x_i}^2 + 2 \sum_{i<j} \left(\frac{\partial y}{\partial x_i}\right)\left(\frac{\partial y}{\partial x_j}\right) s_{x_i} s_{x_j} r$ where r = the correlation factor when $r = 0$, the second term = 0

Example:

$$f = \frac{Pr}{t} \qquad \hat{f} = \frac{\bar{P}\,\bar{r}}{\bar{t}} \qquad \hat{s}_f = \left(\left(\frac{\partial f}{\partial P}\right)^2 s_p^2 + \left(\frac{\partial f}{\partial r}\right)^2 s_r^2 + \left(\frac{\partial f}{\partial t}\right)^2 s_t^2\right)^{1/2}$$

performing the differentiation:

$$= \left(\left(\frac{\bar{r}}{\bar{t}}\right)^2 s_p^2 + \left(\frac{\bar{P}}{\bar{t}}\right)^2 s_r^2 + \left(-\frac{\bar{P}\,\bar{r}}{\bar{t}^2}\right)^2 s_t^2\right)^{1/2}$$

*For more complex expressions use the Monte Carlo simulation technique.

Reliability associated with K_p factors and sample size for estimated joint distribution (f') with 90% confidence.

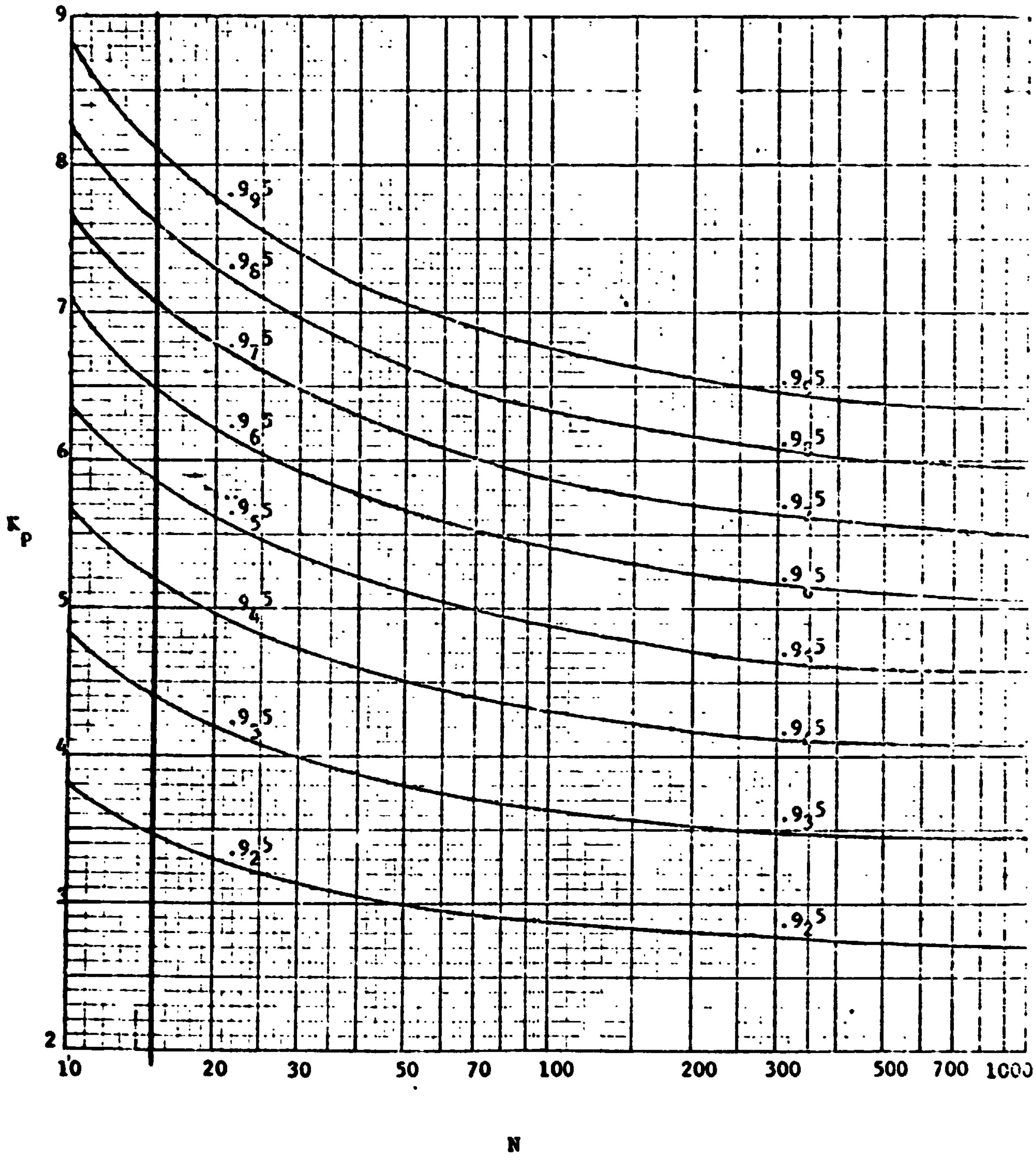
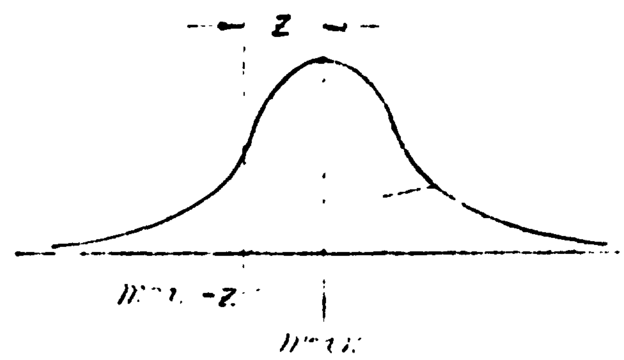


Figure 3

4.2

Figure 4

TABLE OF SINGLE SIDED AREAS OF THE GAUSSIAN DISTRIBUTION



Area represents probability of being above mean $- Z\sigma$ std. deviations.

Z	0	.1	.2	.3	.4	.5	.6	.7	.8	.9
2	.9773	.9821	.9861	.9893	.9918	.9938	.9953	.9965	.9974	.9981
3	.9986	.9990	.9993	.9995	.9997	.9998	$.9_{3}84$	$.9_{3}89$	$.9_{4}28$	$.9_{4}52$
4	$.9_{4}78$	$.9_{4}79$	$.9_{4}87$	$.9_{5}15$	$.9_{5}46$	$.9_{5}66$	$.9_{5}79$	$.9_{5}87$	$.9_{6}21$	$.9_{6}52$
5	$.9_{6}71$	$.9_{6}83$	$.9_{7}00$	$.9_{7}42$	$.9_{7}67$	$.9_{7}81$	$.9_{7}89$	$.9_{8}40$	$.9_{8}67$	$.9_{8}82$
6	$.9_{9}01$	$.9_{9}47$	$.9_{9}72$	$.9_{9}85$	$.9_{10}22$	$.9_{10}60$	$.9_{10}80$	$.9_{10}90$	$.9_{11}48$	$.9_{11}74$

Example: The value of Z required to be 99% certain that a value will be above a (mean $- Z\sigma$) is:

$$2.3 + .10 \frac{(.99-.9893)}{(.9918-.9893)} = 2.327$$

Figure 4

TOLERANCE FACTORS FOR NORMAL DISTRIBUTIONS

Factors K such that the probability is γ that at least a proportion $1 - \alpha$ of the distribution will be less than $\bar{x} + Ks'$ (or greater than $\bar{x} - Ks'$), where $\bar{x}$ and s' are estimates of the mean and the standard deviation* computed from a sample of size n

	confidence limit $\gamma = 0.75$ (1- Probab(k_1))					$\gamma = 0.90$					$\gamma = 0.95$			99%		$\gamma = 0.99$				
n \ α	0.25	0.10	0.05	0.01	0.001	0.25	0.10	0.05	0.01	0.001	0.25	0.10	0.05	0.01	0.001	0.25	0.10	0.05	0.01	0.001
3	1.464	2.501	3.152	4.396	5.805	2.602	4.258	5.310	7.340	9.651	3.804	6.158	7.655	10.552	13.857					
4	1.256	2.134	2.680	3.726	4.910	1.972	3.187	3.957	5.437	7.128	2.619	4.163	5.145	7.042	9.215					
5	1.152	1.961	2.463	3.421	4.507	1.698	2.742	3.400	4.666	6.112	2.149	3.407	4.202	5.741	7.501					
6	1.087	1.860	2.336	3.243	4.273	1.540	2.494	3.091	4.242	5.556	1.895	3.006	3.707	5.062	6.612	2.849	4.408	5.409	7.334	9.540
7	1.043	1.791	2.250	3.126	4.118	1.435	2.333	2.894	3.972	5.201	1.732	2.755	3.399	4.641	6.061	2.490	3.856	4.730	6.411	8.348
8	1.010	1.740	2.190	3.042	4.008	1.360	2.219	2.755	3.783	4.955	1.617	2.582	3.188	4.353	5.686	2.252	3.496	4.287	5.811	7.566
9	0.984	1.702	2.141	2.977	3.924	1.302	2.133	2.649	3.641	4.772	1.532	2.454	3.031	4.143	5.414	2.085	3.242	3.971	5.389	7.014
10	0.964	1.671	2.103	2.927	3.858	1.257	2.065	2.568	3.532	4.629	1.465	2.355	2.911	3.951	5.203	1.954	3.048	3.739	5.075	6.603
11	0.947	1.646	2.073	2.885	3.804	1.219	2.012	2.503	3.444	4.515	1.411	2.275	2.815	3.852	5.036	1.854	2.897	3.557	4.828	6.284
12	0.933	1.624	2.048	2.851	3.760	1.188	1.966	2.448	3.371	4.420	1.366	2.210	2.736	3.747	4.900	1.771	2.773	3.410	4.633	6.032
13	0.919	1.606	2.026	2.822	3.722	1.162	1.928	2.403	3.310	4.341	1.329	2.155	2.670	3.659	4.787	1.702	2.677	3.290	4.472	5.826
14	0.909	1.591	2.007	2.796	3.690	1.139	1.895	2.363	3.257	4.274	1.296	2.108	2.614	3.585	4.690	1.645	2.592	3.189	4.337	5.651
15	0.899	1.577	1.991	2.776	3.661	1.119	1.866	2.329	3.212	4.215	1.268	2.068	2.566	3.520	4.607	1.596	2.521	3.102	4.222	5.507
16	0.891	1.566	1.977	2.756	3.637	1.101	1.842	2.299	3.172	4.164	1.242	2.032	2.523	3.463	4.534	1.553	2.458	3.028	4.123	5.374
17	0.883	1.554	1.964	2.739	3.615	1.085	1.820	2.272	3.136	4.118	1.220	2.001	2.486	3.415	4.471	1.514	2.405	2.962	4.037	5.265
18	0.876	1.544	1.951	2.723	3.595	1.071	1.800	2.249	3.106	4.078	1.200	1.974	2.453	3.370	4.415	1.481	2.357	2.906	3.961	5.167
19	0.870	1.536	1.942	2.710	3.577	1.058	1.781	2.228	3.078	4.041	1.183	1.949	2.423	3.331	4.364	1.450	2.315	2.855	3.893	5.078
20	0.865	1.528	1.933	2.697	3.561	1.046	1.765	2.208	3.052	4.009	1.167	1.926	2.396	3.295	4.319	1.424	2.275	2.807	3.832	5.000
21	0.859	1.520	1.923	2.686	3.545	1.035	1.750	2.190	3.028	3.979	1.152	1.905	2.371	3.262	4.276	1.397	2.241	2.768	3.776	4.932
22	0.854	1.514	1.916	2.675	3.532	1.025	1.736	2.174	3.007	3.952	1.138	1.887	2.350	3.233	4.238	1.376	2.208	2.729	3.727	4.866
23	0.849	1.508	1.907	2.665	3.520	1.016	1.724	2.159	2.987	3.927	1.126	1.869	2.329	3.206	4.204	1.355	2.179	2.693	3.680	4.806
24	0.845	1.502	1.901	2.656	3.509	1.007	1.712	2.145	2.969	3.904	1.114	1.853	2.309	3.181	4.171	1.336	2.154	2.663	3.638	4.755
25	0.842	1.496	1.895	2.647	3.497	0.999	1.702	2.132	2.952	3.882	1.103	1.838	2.292	3.158	4.143	1.319	2.129	2.632	3.601	4.706
30	0.825	1.475	1.869	2.613	3.454	0.966	1.657	2.080	2.884	3.794	1.059	1.778	2.220	3.064	4.022	1.249	2.029	2.516	3.447	4.508
35	0.812	1.458	1.849	2.588	3.421	0.942	1.623	2.041	2.833	3.730	1.025	1.732	2.166	2.994	3.934	1.195	1.957	2.431	3.334	4.364
40	0.803	1.445	1.834	2.568	3.395	0.923	1.598	2.010	2.793	3.679	0.999	1.697	2.126	2.941	3.866	1.154	1.902	2.365	3.250	4.255
45	0.795	1.435	1.821	2.552	3.375	0.908	1.577	1.986	2.762	3.638	0.978	1.669	2.092	2.897	3.811	1.122	1.857	2.313	3.181	4.168
50	0.788	1.426	1.811	2.538	3.358	0.894	1.560	1.965	2.735	3.604	0.961	1.646	2.065	2.863	3.766	1.096	1.821	2.296	3.124	4.096

* s' is the square-root of the unbiased estimate of the variance (*cf.* Sec. 8.7).

Figure 5

4.30

```
[illegible]
100      [illegible] FYSI(50), D(5)
110      [illegible]
120      [illegible](//" [illegible] A RANGE OF [illegible] ALL [illegible]"/
130      &" [illegible] PER [illegible]-1"//)
140      [illegible] INPUT,[illegible](K),FIYI(K),FIYSI(K),K=1,N),D(1),
160      & D(2),FIY[illegible],FIYJ,FM,FF,VF,VB,VI
170      [illegible] FORMAT(" INPUT VALUES [illegible]"/" [illegible]"/" [illegible], FIY, SIGFIY, [illegible]
175      & [illegible] 50)"/
180      &" D(1),D(2),"/" FIY[illegible],FIY[illegible],FM,FF"/" VF,[illegible],VI, [illegible]
185      [illegible] VI=SI(1/1)"//)
190      [illegible] 100 [illegible]=1,[illegible]
200      FIY=FIYI([illegible]): SIGFIY=FIYSI([illegible])
210      [illegible]
215      [illegible]=FIY-[illegible](FIY**2-(1.- F**2)*(FIY**2- F**2*SI(FIY**2))/
220      & (1.-[illegible]F**2)
230      SIGF=F*SQRT([illegible])
240      XMS=.85*(FIY-FIYM*SIGFIY)/(F+FM*SIGF)-1.
240      FN=(SIGFIY**2+SIGF**2)**2/(SIGFIY**4/FIYN)
250      DO 100 I=1,[illegible]
260      [illegible]=.01
270      DO 100 J=1,1[illegible]
280      [illegible]=[illegible]+.002
290      [illegible]=D(I)-1/[illegible].
300      [illegible]*[illegible]/.
306      SIGF=[illegible]
310      IF (J-1) 2,3,5
320   3  [illegible],SIGF,[illegible],SIGF,[illegible]
330   4  FORMAT(//[illegible],"[illegible]",4X,"F",/X,"SIGF",[illegible]," ",[illegible],"I",[illegible]
340      &"[illegible]",[illegible],"SIG[illegible]",[illegible],"[illegible]",[illegible],"[illegible]",[illegible],"[illegible]LI[illegible]",/[illegible],F5.[illegible],
350      & F7.[illegible],F[illegible].[illegible],F7.3,F7.0,F6.0,F5.2,F5.0)
360      GO TO 100
370   5  PRINT 6, [illegible], [illegible], [illegible], SIG[illegible]
380   6  FORMAT([illegible]3X, [illegible]F7.3, F7.[illegible],F6.0)
390 100  CONTINUE
400      [illegible]
```

[illegible]

[illegible] 001. [illegible] 8[illegible]0.[illegible] 10[illegible] [illegible].71 [illegible]

[illegible] 1976 [illegible]

Figure 6

4.31

FILE NAME=ACL[illegible]-3

[illegible] 15:5[illegible] 18/09/[illegible]9

[illegible] DELTA P FOR A RANGE OF MEAN WALL TEMPS,
[illegible] RADIUS AND THICKNESS PER [illegible])-C-1

[illegible] VALUES FOR

[illegible], SIG[illegible], ([illegible] 1) 50)
[illegible](1), [illegible]),
[illegible]
[illegible] VP=SIG(P/[illegible], V[illegible]=SIG(/[illegible], VT=SIG(T/T)
[illegible] 1
[illegible] 1[illegible] [illegible] 1670
[illegible] .1[illegible] .[illegible]
[illegible]
[illegible] .1 .[illegible]2 .[illegible]

L[illegible]	P	SIGP	R	T	P	SIGP	S	FN	[illegible]
1[illegible]6.	944[illegible].	[illegible]3.	0.171	0.01[illegible]	663.	7.	0.53	17.	.9,40
			0.170	0.014	77[illegible].	[illegible]			
			0.169	0.01[illegible]	894.	[illegible]			
			0.16[illegible]	0.01[illegible]	1012.	1[illegible]			
			0.167	[illegible]	1131.	11.			
			0.16[illegible]	0.[illegible]	1[illegible]51.	1[illegible]			
			0.165	[illegible]	1373.	14.			
			0.164	0.0[illegible]	1497.	1[illegible]			
			0.163	.0[illegible]	16[illegible].	16.			
			0.16[illegible]	0.03[illegible]	1749.	17.			
			0.161	0.032	1877.	19.			
			0.160	0.034	2007.	[illegible]			
			0.159	[illegible]	213[illegible].	[illegible]1.			
			0.15[illegible]	0.03[illegible]	[illegible]71.	[illegible]			

L[illegible]	P	SIG[illegible]	[illegible]	T	P	SIG[illegible]	[illegible]	FN	[illegible]
1[illegible]9.	944[illegible].	4[illegible]3.	0.27[illegible]	0.01[illegible]	408.	4.	0.53	17.	.9,40
			0.277	0.014	[illegible]77.	5.			
			0.27[illegible]	0.01[illegible]	547.	[illegible]			
			0.[illegible]75	0.01[illegible]	618.	6.			
			0.27[illegible]	0.0[illegible]	6[illegible]9.	7.			
			0.273	0.0[illegible]	761.	[illegible]			
			0.27[illegible]	0.0[illegible]	833.	[illegible]			
			0.[illegible]	0.026	906.	[illegible]			
			0.270	0.0[illegible]	97[illegible].	10.			
			0.[illegible]69	0.030	105[illegible].	11.			
			0.[illegible]68	0.03[illegible]	11[illegible]7.	11.			
			0.[illegible]67	0.03[illegible]	120[illegible].	1[illegible]			
			0.[illegible]66	0.03[illegible]	1[illegible]7[illegible].	1[illegible]			
			0.[illegible]65	0.03[illegible]	1354.	14.			

4.32

Figure 7

M E M O R A N D U M

To: Distribution | Date: 29 December 1969
7850:0395M

From: W. M. Bryan

Subject: Transmittal of NRP 301, "Component Failure-Mode Analysis for the NERVA Engine, Instructions for"

Copies To: D. Buden, W. E. Campbell, J. W. Conant, A. D. Cornell, D. S. Duncan, W. E. Durkee, C. W. Funk, R. B. Glasscock, D. Holzman, G. S. Kaveney, J. M. Klacking, C. K. Leeper, C. F. Leyse, B. Mandell, I. L. Odgers, J. H. Ramsthaler, K. Sato, L. A. Shurley, File

NTO: W. H. Bushnell

Reference: (a) NRP 300, System Failure-Mode Effect and Criticality Analysis
(b) Memo 7850:M0256, W. M. Bryan to Distribution dtd 19 August 1969, subj: "Review of NERVA Program Procedure NRP 300, Failure Mode, Effect and Criticality Analysis for Components of the NERVA Engine, Instructions for"

Enclosure: (1) NRP 301, Component Failure-Mode Analysis

Enclosure (1) is the initial draft of the Component Failure-Mode Analysis (FMA) which is transmitted for your review and implementation into the NERVA design and analysis process. The FMA, together with the system level procedure described in Reference (a), supersedes the single procedure defined in Reference (b). The single analysis system has proven to be unwieldy.

The analysis process is initiated with the system level study, Reference (a), to determine system effects and interactions and, among other things, provide a basis for selection of component concepts which preclude critical system failure modes. Each Failure-Mode Effect and Criticality Analysis involves system and design engineering groups which have the expertise necessary to understand the engine requirements and the system and subsystem interaction effects when these requirements are not met by the components. The Component Failure-Mode Analysis level study, Enclosure (1), is initiated by the designer upon completion of the system level study to determine the cause of failures within a component. It is at this level that stress, materials, radiation, thermal, instrumentation and controls, and quality assurance are formally included in the analysis process. Also, probabilistic analyses are conducted on causes of failure identified in the component study.

W M Bryan
W. M. Bryan, Supervisor
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
W M Bryan 12/?/69
CLASSIFYING OFFICER DATE

NERVA PROGRAM RELIABILITY PROCEDURES

Title	N.R.P. Number
Component Failure-Mode Analysis for the NERVA Engine, Instructions for	301
	Supersedes N.R.P. No. N/A
	Date

1.0 PURPOSE

The purpose of this procedure is to establish the criteria for Component Failure-Mode Analysis (FMA) and define responsibilities for their preparation and utilization in the design of components for the NERVA engine. It establishes a uniform means for preparing FMAs by applying a coordinated systematic approach to failure identification at the part failure mechanism level and evaluation of its causes. The requirement for this procedure is set forth in Data Item R-101, NERVA Reliability Program Plan.

For the NERVA program, this document supersedes and obsoletes all portions of NRO Program Directive No. RN-PD-S-1074, and Amendment A (2.1 and 2.2) and WANL Procedures RMP 3-5 (2.3).

2.0 APPLICABLE DOCUMENTS

2.1 RD-PD-S-1074, Failure Mode Analysis - REON, Instructions for, dated 22 December 1966.

2.2 RN-PD-S-1074A, Failure Mode Analysis - NRO, Amendment to, dated 3 March 1967.

2.3 WANL RMP 3-5, Failure Mode Effect and Criticality Analysis.

2.4 NRP-300, System Failure-Mode, Effect and Criticality Analysis for the NERVA Engine, Instructions for.

Approved By: Issue Date ______________

Manager, Reliability NERVA Program Manager

AEROJET-GENERAL CORPORATION

2.0. Applicable Documents (cont.)

2.5 Data Item R-101, NERVA Reliability Program Plan

2.6 Data Item C-018, NERVA Configuration Management Plan

3.0 POLICY

3.1 Component Failure-Mode Analysis (FMA) will be used as an integral part of the design process for the NERVA engine. The high cost of testing the NERVA engine precludes extensive engine system reliability testing to demonstrate the stringent reliability requirements. The FMA is a primary tool whereby reliability can be an effective design parameter.

3.2 The basic objective of the component FMA is to provide the basis for analyzing a design in order to assure a systematic and detailed review of all of the possible ways that a component can fail to perform its design functions. An assessment of the probability of failure of each part at the failure mechanism level provides a basis for decisions which can maximize the probability of a reliable component. It assures that all feasible actions are taken to minimize the probability of failure occurrence and/or to minimize the effects of the failure. It also provides the following:

3.2.1 A basis for comparing the reliability of design alternatives during the concept definition phase.

3.2.2 A basis for the analytical prediction of the reliability of the design during all phases of design development (i.e., concept selection, detail design, development testing, qualification) and during actual use.

3.2.3 A basis for recall of the analytical techniques used to assess the structural dynamic and performance integrity of components.

3.0. Policy (cont.)

3.2.4 A record of design analysis by program special talents (stress, materials, radiation effects, thermal, system and quality and reliability analysts) and of the impact of these analyses on the design features and fabrication processes.

3.2.5 Information for statistical planning of tests.

3.2.6 A checklist for design reviews, test plan reviews and the evaluation of design and fabrication changes introduced during production to assure that such changes to not degrade reliability by violating design criteria.

3.3 The FMA will be initiated and maintained as an integral part of the entire design process. It will be continually updated as design analyses are conducted. The cognizant design organization will initiate and be responsible for the component FMA with the assistance and approval of Reliability. It will be reviewed by other engineering disciplines and comments will be documented to assist in design decisions. Detail responsibilities are set forth in Section 7.0.

4.0 DEFINITIONS

4.1 COMPONENT FAILURE-MODE ANALYSIS

A component Failure-Mode Analysis (FMA) is a method of identifying and assessing the probability of occurrence of all possible means by which a component can fail to perform its required functions. It is also a systematic procedure for identifying all of the primary causes (mechanisms) of each mode of failure and eliminating from further consideration those which do not have adverse system effects as evaluated in a system FMECA or those which, in the judgement of engineering, do not require detailed analysis due to inherently high margins of safety of the mechanism of failure. A major emphasis is placed on identification of those means by which human or process

4.1, Component Failure-Mode Analysis (cont.)

errors cause a mode of failure to occur. In a component design analysis, the identified critical failure modes will be further investigated by detailing all of the procedures for analysis of each cause. Each mechanism of failure will be analyzed in the generic terms of the "Failure Causing Stress" and the "Failure Resisting Strength" where possible. These include, but are not limited to, structural, electrical, performance, dynamic, and environmental stresses and strengths. Where possible, the nominal level and expected variation in these "stress" and "strength" values provides the vehicle for assessing the probability of success of the design concept. The detailed methods for calculating these "stress" and "strength" values will be described in separate reliability procedures.

4.2 FAILURE-MODE EFFECT AND CRITICALITY ANALYSIS (FMECA)

A FMECA is an analytical technique which documents all possible failure modes in a system design, determines through engineering evaluation the critical failure modes relative to mission success, documents the reasons for classification of other modes as noncritical. In addition to identification of critical failure modes, it also identifies major subsystem interactions and important component interactions at the subsystem level. For details of an FMECA, refer to NRP 300.

4.3 STRENGTH

Strength, or part capability, is defined as the ability of a part to resist failure or, more exactly, "it is the maximum allowable value of a failure governing stress". Strength is measured in terms of the pertinent mechanical or physical properties of the material.

4.4 STRESS

Stress, or failure inducing characteristic, of a part, is defined as the summation of those factors of storage, usage or test which tend to affect the ability of the component to perform a required function. Stress may be calculated by any analytical technique which has been defined as a means to assess a failure mechanism.

4.5 FAILURE MODE

A failure mode is the description of the presumed way in which a component ceases to perform an intended function within specified performance limits. (A failure mode is a specific required function expressed negatively.)

4.6 FAILURE-MODE EFFECT

A failure-mode effect is a description of the expected change in all other components in a system or change in system integrity, operation or performance which results from the defined failure mode. A failure mode effect may carry through successively higher assemblies to the total system and will be assessed at all levels of assembly.

4.7 FAILURE MECHANISM

A failure mechanism is the process, or measure, of a failure described in terms of the stress or the combination of stresses and/or environmental factors which exceed the resisting strength attributes of a part. Failure mechanism should be described at a level that specifically identifies or describes an engineering analysis which can be utilized to compute reliability. Similar mechanisms should be combined only when environment, loads, etc., are

4.7. Failure Mechanism (cont.)

dependent and where appropriate analytical tools are available (or can readily be developed) for application to the analysis of the combined mechanisms.

4.8 ENVIRONMENTAL FACTORS

Those factors which make up the total exposure of an item (part, component or subassembly) during its manufacture, storage and service life. Environmental factors may influence the imposed stress or the strength of an item, or both. These influences may be additive and/or accumulative, temporary, or permanent. They include temperature, pressure, acceleration, atmospheric conditions, moisture, corrosive materials, radiation, vibration, magnetism, etc., and may be at a steady-state or transient condition.

5.0 PROCEDURE

The FMA will be initiated during the design concept selection phase and will be updated as the sophistication of the design analysis is increased. The FMA will be formally reported as a part of the Allocation, Prediction and Assessment Reports, R-202. The content of the analyses will be affected by program status and the amount of design detail available at the time of the various program milestones where an Allocation, Prediction and Assessment Report is required.

5.1 COMPONENT DEFINITION

The physical and functional limits of the components, the inputs to the component, the outputs required of the component and the environment in which it is manufactured, stored and used, are all part of the component definition needed for the FMA. The state of design definition expected at each R-202 milestone for the NERVA program is as specified in the NERVA Configuration Management Plan which is summarized below.

5.1, Component Definition (cont.)

Changes in the amount of available design definition will have a corresponding effect on the detail available in the failure mode analysis.

5.1.1 Design Requirements Baseline (DRB) - A review of Part I CEI and ECC specification to justify the performance and design requirements therein.

5.1.2 Preliminary Design Review (PDR) - A formal technical review to show that the selected design approach is compatible with requirements of the Part I specifications.

5.1.3 Critical Design Review (CDR) - A formal technical review to establish the design configuration of the CEIs and ECCs which will be subjected to formal qualification tests. The CDR will be conducted when the detail design is complete and the results from the development test program are available.

5.1.4 Formal Qualification Review (FQR) - The FQR will be a formal technical audit to verify that all of the performance and design requirements delineated in Section 3 of the Part I specifications (CEI and ECC) have been successfully demonstrated in accordance with the requirements defined in Section 4 of the Part I specifications.

5.1.5 First Article Configuration Inspection (FACI) - FACI is a formal customer audit to verify that the as-manufactured hardware complies with the configuration defined by the Part II Detail Specification. The audit also establishes the exact relationship between the configuration of the end item qualified and the configuration of the end item released for production.

5.2 FAILURE MODES WORKSHEETS (FIGURES 1, 2 and 3)

The FMA assumes that only the failure under consideration has occurred. When redundancy is noted within the component being analyzed (i.e., failure of more than one nozzle tube required for nozzle failure) this effect is considered in the failure probability model for the failure mode. Where redundancy or failure interactions are noted at higher system levels, this fact is noted in the effects analysis for use in the system FMECAs from which the overall reliability predictions are made. The analysis of a failure mode will include all credible mechanisms that might cause the failure mode. The probability of failure occurrence of each mechanism will be assessed by the designer either by stress/strength analysis or by the most rigorous technique available. This evaluation will be reviewed by other program talents and either substantiated or modified by the designer as a result of the reviews. This process will be documented at the component level on the enclosed form using the following procedure.

5.2.1 Figure 1 - Component Failure Mode Analysis

5.2.1.1 Column 1 - Failure Mode Identification Number

5.2.1.2 Column 2 - Component Mode of Failure

The component mode of failure should negatively describe a component function (see Section 4.5). The level of the component part analyzed depends upon the interdependence of part of subparts, as well as the physical or engineering boundaries usually associated with the part. This column will be prepared by the component designer with assistance of reliability engineers and reviewed by the various program talents.

5.2, Failure Modes Worksheets (Figures 1, 2 and 3) (cont.)

5.2.1.3 Column 3 - Mechanism Identification Number

This is a code number for each component failure mechanism which increases numerically as additional mechanisms are identified. The purpose is to key the various pages of the FMECA together. Some analyses on an individual mechanism of failure will be on succeeding pages and a common tie-in is necessary.

5.2.1.4 Column 4 - Component Mechanism of Failure

These are the mechanisms which cause the mode of failure described in Column 2. These will be filled in initially by the designers and added to by the subsequent analysts if additional mechanisms are identified. Component mechanisms will be identified primarily on the basis of past experience refined to reflect (a) engine configuration, (b) comparative environments, and (c) NERVA duty cycle requirements. Each mechanism will be analyzed in detail by all personnel participating in the failure mode analysis. Therefore, mechanisms of failure should be defined in terms which relate to the method of analysis required.

5.2.1.5 Column 5 - Mission Phase

Mission Phase sensitivity to failure mechanisms should include chilldown, startup, steady-state, shutdown, cooldown and coast.

5.2. Failure Modes Worksheets (Figures 1, 2 and 3) (cont.)

5.2.1.6 Column 6 - Environmental Factors

In this column the designer lists the environments which have an effect on the mechanism of failure. Environments during the entire life of the part should be reviewed, including the manufacturing processes, assembly, testing, shipping, storage and operational use. Tables I and II list typical environments which may be applicable.

5.2.1.7 Column 7 - Stress Considerations

In this column the designer relates the stress which may induce failure to the specific analyses required to completely evaluate the mechanism of failure which may be induced by the part design and environmental exposure. Table I lists some factors which can effect the failure inducing stress of parts.

5.2.1.8 Column 8 - Strength Considerations

In this column the designer notes the "failure resisting strength" which must be evaluated in order to determine the part resistance to the stress and resulting mechanism of failure. Table II lists some factors which can effect the failure resisting strength.

5.2.1.9 Column 9 - Design Analysis

In this column the designer summarizes his analysis in terms of the expected probability of occurrence of the modes of failure by each mechanism. The more comprehensive and detailed this analysis is, the more valuable the FMA becomes. As the design progresses, the FMA will be upgraded and the design analysis will be more detailed and specific.

5.2, Failure Modes Worksheets (Figures 1, 2 and 3) (cont.)

During conceptual trade studies it may be desirable to have a quantitative reliability assessment for each mode of failure in order that they may be summed for an overall comparison of the various alternates. The values may be derived by selected previous component test experience, or if no test experience is available, by a qualitative rating system based on engineering judgement.

In the early analyses, these columns will be general discussions of previous experience, such as: "Traditionally, designs are producing factors of safety of >2.0 on hoop stress, primarily because wall thickness, in practice, is heavier than minimum allowable by hoop stress equations" or; "Tolerance on dimension on this area is easily measured and no subsequent manufacturing processes which are expected to effect dimension are required"; or "Tolerance on surface finish is difficult to maintain and can only be measured in localized areas", etc.

An analysis progresses to specific designs, these columns will summarize the results of structural calculations, such as "Maximum stress is expected at location 'B' with a mean of 20,000 psia and sigma of 2000 psi, 347 stainless steel forging at 150°R has a normal standard deviate of 9.8 and reliability $>9_{23}$ SNPO-C-1 Margin of Safety is ...., etc.

The analyst must sign the analysis so that he can be contacted directly to provide additional information or resolve questions should such be needed during design reviews.

5.3 FIGURE 2 - ENGINEERING ANALYSIS OF MECHANISMS

This worksheet is provided with a copy of each completed Figure 1 to the various technical disciplines that will review the FMA. These figure will not be retained as a permanent part of the failure mode analysis. The work-

5.3, Figure 2 - Engineering Analysis of Mechanisms (cont.)

sheet presented is only a guide--other formats may be used if deemed necessary. The objective of these reviews is to identify or emphasize problems associated with each mechanism and to define the studies being done in the specialty areas which have a bearing on each mechanism of failure. By rigorously insisting on an analysis of each mechanism of failure by all specialties, the program minimizes the possibility that no critical analysis or test program is overlooked. In early issues of the FMA, the specialty analyses may refer to prior studies which support their conclusions, or development efforts that are required to obtain the analytical techniques or test data to assure there is no reliability problem. As the development effort proceeds, the analysis will be changed to reflect the additional supporting data which have been acquired.

5.3.1 <u>Column 1 - Component Failure Mechanisms Identification Number</u>

5.3.2 <u>Column 2 - Summary of Failure Mode and Mechanism</u>

Engineering specialists reviewing the FMA may elect to mark up Figure 1 of the FMA with his suggested addition or deletion to the failure mechanism (Figure 1, Column 4), or he may rewrite them on Figure 2 in this column.

5.3.3 <u>Columns 3 and 4 - Column Headings are Self-Explanatory</u>

Check lists may be developed as an aid for each discipline answering typical questions in relation to each mechanism of failure.

5.4 FIGURE 3 - SUMMARY OF SUPPORT ENGINEERING ANALYSIS

This summary sheet will present a compilation of the information gathered on the Figure 2 worksheets and will be included in the FMECA presentation in Data Item R-202.

5.4.1 Column 1 - Failure Mechanism Identification Number

This column corresponds to the identification number in Column 3, Figure 1, and is used to key the analyses together.

5.4.2 Columns 2 through 7

Detailed analyses by the indicated program talents will be summarized in these columns. The Reliability Analysis will include the failure rate for each failure mechanism. The allocated and estimated reliabilities for the component will be entered at the top of the first sheet of Design Engineering Analysis, Figure 1. The latter values will be based on the summation of the failure rates of the mechanisms.

6.0 APPLICABILITY

6.1 An FMA shall be prepared as specified herein for each of the following components and assemblies shown in the specification tree of the NERVA Engine CEI Specification Part I (Reference C).

6.1.2 Any subsystem or assembly which is not broken into lower tier components in the specification tree.

6.0. Applicability (cont.)

6.2 DRB

A preliminary system level FMECA component level FMA will be completed by Reliability for DRB based on the DRB Reference Engine and Trade Study results. The Reference Engine will consist of component concepts and preliminary layouts. Historical failure rate data and/or qualitative techniques, such as Appendix A, will be used to obtain reliability values for each mode of failure. These data will be derated as appropriate to account for differences in design or environments. The FMECA and FMA model reliability values will then be combined in mathematical models to compute engine system reliability. Detailed procedures for preparation of the system FMECA will be documented in NRP 300.

6.2.2 PDR

6.2.2.1 Engine PDR

Revise DRB system level analysis and add system effects and criticality analysis. Include any revised reliability values obtained from available component FMECAs.

6.2.2.2 Component PDR

Compilation of component failure modes, in accordance with this procedure, will be completed for PDR, based on the candidate design evolved to meet the requirements set forth at DRB. Historical failure rate data may be utilized at the component level with appropriate derating factors. Stress and strength approximate calculations will made, where possible, assuming nominal values and variance where the variables data are not readily available. A detailed review of each failure mode will be made by the various program technical disciplines to verify failure mode identification and

6.2, PDR (cont.)

probability of occurrence. A parallel effort will be made during and subsequent to the PDR FMA iteration to develop detailed procedures for calculating reliability and, where applicable, to develop computer programs which will calculate stress.

Those failure modes considered critical to mission success will be clearly identified and those which have been eliminated will be docu-emnted with supporting analysis by the program specialists.

6.3 FQR

(TBD)

6.4 FACI

(TBD)

7.0 <u>RESPONSIBILITIES</u>

7.1 ENGINEERING

7.1.1 The cognizant design organization will be responsible for the following:

7.1.1.1 Initiating failure mode analyses as soon as candidate designs have been sketched in sufficient detail for study.

7.1.1.2 Preparation of Figure 2 of the component FMA and updating and expanding these analyses for surviving candidates as the sophistication of the design increases.

7.1. Engineering (cont.)

7.1.1.3 Assessing implications of reviews by various program specialties and initiating design changes as appropriate to eliminate unreliable features disclosed by the FMA, or conducting tests, as necessary, to assess failure mechanisms for which no satisfactory analysis has been found.

7.1.1.4 Make decision as to which failure modes are to be used in reliability prediction.

7.1.1.5 Determine when analysis is satisfactory for incorporation into an R-202 for a formal design review.

7.1.2 Stress, Materials, Radiation and Thermal Engineering will be responsible for the following functions:

7.1.2.1 Review each mode and mechanism of failure to determine whether all input effects have been properly considered, what data are available and what will be available to use in the analysis of failure modes.

7.1.2.2 Add failure modes and/or mechanisms of failure which have been overlooked.

7.1.2.3 Modify failure modes and mechanisms to reflect data available to their particular specialty.

7.1.2.4 Identify or emphasize problems associated with each mechanism.

7.1.2.5 Define studies being done or needed in their specialty area which have a bearing on each mechanism of failure.

7.1, Engineering (cont.)

7.1.2.6 Identify data which is available or required to the analysis of each failure mechanism.

7.1.2.7 Summarize the results of their analysis on the Failure Modes Worksheet, Figure 2.

7.2 RELIABILITY ENGINEERING

Reliability will participate in the failure mode analysis cycle as technical consultants, coordinators and as auditors for overall adequacy. To perform these functions, they are responsible for the following:

7.2.1 Provide training to all program talents on failure mode analysis techniques.

7.2.2 Prepare procedures for means to predict reliability from all types of failure modes.

7.2.3 Assist designers in initial preparation of failure modes and mechanisms.

7.2.4 Coordinate analysis by program specialists and assist as necessary to assure comprehensive studies in all areas.

7.2.5 Conduct effects and criticality analysis.

7.2.6 Recommend to designers failure modes which should be used to assess reliability, procedures to be used for reliability assessment and any required testing.

7.2, Reliability Engineering (cont.)

7.2.7 Approve FMA after Design has submitted it for incorporation into Data Item R-202.

7.3 QUALITY ENGINEERING

Quality Engineering will be responsible for the following:

7.3.1 Review of applicable failure modes and mechanisms for adequacy.

7.3.2 Evaluation of available quality control methods for detecting/ preventing the occurrence of each failure mechanism.

7.3.3 Development of new methods and improvement of existing methods of quality control when the FMA indicates such action will improve the reliability of a part of component.

7.3.4 Documenting their evaluation on an FMA worksheet.

7.4 SYSTEMS ENGINEERING

Systems Engineering will be responsible for the following:

7.4.1 Review of each failure mode and its effect upon the system.

7.4.2 Assure all requirements have been considered in the analysis.

7.4.3 Look for system interaction effects which require additional analysis at the component level.

7.4.4 Assure all interface effects between components have been properly considered.

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MODES ANALYSIS

Design Engineering Analysis

SYSTEM ______ SUBSYSTEM ______ DRAWING NO. ______

PREPARED BY ______ DEPT. ______ EXT. ______ ISSUE DATE ______

APPROVED BY ______ PAGE ______ OF ______

No.	Component Mode of Failure	Item Ident No.	Component Mechanism of Failure	Mission Phase	Environmental Factors	Stress	Strength	Design Analysis
Serial Numbering System	Negative description of component function.	Code No. for Failure Mechanism	Mechanisms which cause the mode.	Mission Phase applicable to failure mode and mechanism.	Environment which may have an effect on the mechanism.	The stress which may induce failure relates to the specified analyses required to evaluate mechanisms.	Failure resisting strength.	Summary of analysis in terms of the expected probability of occurrence of the mode by each mechanism.

NRP 301
Figure 1

5/11

NRP 301
Figure 2

[illegible] ANALYSIS

Engineering Analysis of Mechanisms

SYSTEM ____________ SUBSYSTEM ____________ CONTRACT ____________ DRAWING NO. ____________ ISSUE DATE ____________

PREPARED BY ____________ DEPT ________ EXT. ________ PAGE ______ OF ______

[illegible]	Failure Mode Mechanism	Comments Relative to the Analysis of	
		Stress(es) Causing the Mechanism of Failure	Strength Resisting The Mechanism of Failure
[illegible]	[illegible]	Self Explanatory	Self Explanatory

NRP 301
Figure 3

Engineering Analyses

SYSTEM ______ COMPONENT ______
SUBSYSTEM ______ DRAWING NO ______
ISSUE DATE ______
PREPARED BY ______ DEPT. ______ EXT. ______ PAGE ______ OF ______

	Quality Analysis	Stress Analysis	Materials Analysis	Radiation Analysis	Thermal Analysis	System Analysis	Reliability Analysis
	Analyst:	Analyst:	Analyst:	Analyst:	Analyst:	Analyst:	Analyst:

SUMMARY OF DETAILED ANALYSIS PERFORMED BY INDICATED SPECIALISTS

TABLE I

FACTORS AFFECTING FAILURE INDUCING STRESSES

Factor	Affect on Stress
1. Pressure	1. A direct cause of stress, usually tensile, but may cause other types as a result of interaction of parts.
1.1 Transient Conditions	
1.1.1 Undirectional	
1.1.2 Cyclic	1.1.2 (a) Cyclic loads may cause fatigue stress. (b) Amplifying effects at resonant frequencies of part(s).
1.2 Steady State Conditions	
1.2.1 Positive pressure	
1.2.2 Zero pressure	1.2.2 "Welding immobilizes moving parts at high vacuum
2. Linear Acceleration/Deceleration	2. (a) Loads imposed = f (mass and acceleration) (b) Impact effects of rapid deceleration.
2.1 Solid Parts	
2.2 Liquids	2.2 (a) Impact effects when liquid flow suddenly stopped by valve closing.
3. Weight	3. Stress from supporting weight of parts and contents.
4. Vibration	4. (a) Increases fatigue stress (b) Amplifying effects at resonant frequencies of parts, assemblies.
4.1 From rotating parts	
4.2 From reciprocating parts	
4.3 From external mechanical sources	
4.4 From external acoustical sources	
5. Flow of Fluids	5. Fluids will erode containing material when flowing at high velocity or when direction of flow is changed abruptly.
5.1 Gases	
5.2 Liquids	

6. Thermal Environment
   6.1 Transient Conditions
      Heat input
      Heat removal
      Cyclic changes
   6.2 Steady State Conditions
      High Temperature
      Low Temperature
      Heat Transfer
   6.3 Sources of Thermal Effects
      LH_2 flow
      GH_2 flow at high temperature
      GH_2 flow at moderate temperature
      Nuclear radiation and interactions
      Solar radiation
      Friction radiation to space between moving parts.

6. (a) Thermal expansion/contraction applies stress to localized areas causing bending, etc.
(b) Differential thermal expansion/contraction between adjacent parts due to material differences.
(c) Differential expansion/contraction between adjacent parts due to temperature differences.
(d) Corrosion rate is a function of temperature (see item 8.1).
(e) Gas pressure and resulting stresses are a function of gas temperature.

7. Manufacturing Factors
   7.1 Dimensional Variation
   7.2 Surface Finish
   7.3 Lack of lubricant
   7.4 Scratches, gouges and nicks
   7.5 Lack of corner radius
   7.6 Welding Errors
   7.7 Contaminants
   7.8 Assembly Errors

7.1 Causes variation in load bearing area.

$$\text{Stress} = \frac{\text{load}}{\text{load bearing area}}$$

7.2, 7.3 Frictional effects on moving parts.

7.4, 7.5 Stress concentration on sharp corner provides and origin point for failure.

7.6 Undercutting, etc., reduces load bearing area

7.7 Blockage of fluid flow effects pressures

7.8 Various effects depending on the assembly details. Examples:
(1) Excess torque over-stresses bolts.
(2) Omission of parts increases loads on other parts.

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8. Chemical Factors	
8.1 Corrosive Materials	8.1 Corrosion reduces load bearing area, increasing stress. Corrosion rate is increased by stress.
8.1.1 Marine air	
8.1.2 Acidic vapors	
8.1.3 Alkaline vapors	
8.1.4 Residual materials from cleaning operations	
8.1.5 Moisture	
8.1.6 System fluids	
8.2 Solar Radiation	8.2, 8.3 See "6. Thermal Factors."
8.3 Nuclear Radiation	
8.4 Sublimation in Space	8.4 Reduction in load bearing area increases stress.

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TABLE II

FACTORS AFFECTING FAILURE RESISTING STRENGTH

Factor	Affect on Strength
1. Vibration	1. Reduces resistance to fatigue failure.
1.1 From Rotating Parts	
1.2 From Reciprocating Parts	
1.3 From External Mechanical Sources	
1.4 From External Acoustical Sources	
2. Thermal Environment and Irradiation	2. Causes changes in material properties:
2.1 Transient Conditions	(a) Strength = $f\left(\frac{1}{\text{temperature}}\right)$
2.1.1 Heat input	(b) Ductility = f (temperature)
2.1.2 Heat removal	(c) Impact resistance = f (temperature)
2.1.3 Cyclic changes	(d) Plastic flow = f (temperature)
2.2 Steady State Conditions	(e) Annealing effects of high temperature
2.2.1 High temperature	(f) Electrical resistance = f (temperature)
2.2.2 Low temperature	(g) Electrical insulation breakdown
2.2.3 Heat transfer	Effects may apply to entire part or to localized areas. Parts may be at uniform temperature or a gradient may exist.
3. Manufacturing	
3.1 Dimensional Variations	3.1 through 3.4 Frictional heating reduces strength and permits galling
3.2 Surface Finish	
3.3 Lack of Lubricants	
3.4 Contaminants	
3.5 Metal Forming	3.5 Cold working increases strength and may cause directional differences in material strength.
3.6 Welding	3.6 Annealing effects in heated areas.
3.7 Heat treating/annealing	3.7 Modifies physical properties
3.8 Electrolytic cleaning	3.8, 3.9 Hydrogen embrittlement
3.9 Electrolytic plating	

3.10 Assembly Errors	3.10 Various effects depending upon details of the assembly. Examples: (1) Torque on bolts affects ability of gasket to prevent leaks (2) Allows heat to contact area not designed for such.
4. Chemical Factors	
4.1 Nuclear Radiation 4.2 Solar Radiation	4.1, 4.2 Chemical changes caused by radiation. For thermal effects see Section 2 above.
4.3 Hydrogen Absorption 4.3.1 During manufacturing 4.3.2 During use	4.3 Hydrogen Embrittlement. Chemical reaction of carbon and hydrogen.
5. Material Variability 5.1 Within a part 5.2 Within a material lot 5.3 Lot to lot	5. Physical properties vary as a result of variations in: (a) Material composition (b) Material manufacturing processes. (c) Part/assembly manufacturing processes (see Section 3 above).

4.5

STATUS REPORT PREPARED FOR

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

5.0 SPECIAL STUDIES

M E M O R A N D U M

TO: L. P. Burke

DATE: 16 July 1969
7850:M0216

FROM: T. W. Klinefelter

SUBJECT: Literature Search on Electronic Control System (EPIC) Failure Rates

DISTRIBUTION: H. Musgrove, J.T.R. Wilson, Section 7850 Personnel

ENCLOSURE: (1) Project Mercury Altitude Control Subsystem Reliability
(2) Atlas "D" Reliability by System

INTRODUCTION

In order to provide background information for the design of the NERVA Electronic power and Instrumentation Control System (EPIC), a literature search was conducted to provide system level failure rate data.

SCOPE OF STUDY

The following summary lists the material reviewed to date:

Reviewed approximately 200 report abstracts from the following sources:

1. Nuclear Science Abstracts - 1964 to present
2. Scientific & Technical Aerospace Report Abstracts 1964 - present
3. Reliability Abstracts & Technical Reviews 1966 - Present

Reviewed 451 citations from NASA literature search #8554 - "Reliability of Missile Electronic Instrumentation and Control Systems"

Reviewed 106 citations from DDC literature search #12632 - "Control Systems Reliability and Failure Data"

Reviewed the following reports distilled from the above sources:

1. Design for Space - Veh. Control System Reliability
2. Rel. Study Equip. & Comp. in Nuclear Power Plants
3. Rel. Summary Reports (Gen.Dyn) Oct. 1961
4. Semi. Annual Report on Prod. Design & Rel. Studies for Airborne Elect. Pack.
5. WS-107A-2 Rad-Inert. Guidance Syst. Fil Sum. Rept. #9
6. Research & Feas. Study to Achieve Rel. in Auto Flt. Control Systems
7. The Reliab. of the Lunar Orbiter Power System

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8. Reliab. Anal. of Modular Power Conditioning and Control Systems for Ion Engines
9. A Reliability Study of a Nuclear Reactor Pressure Monitor Coincidence Trip System.
10. A Control System Study for an in Core Thermionic Reactor
11. Final Report of the Able Star Reliability Program
12. Impact of Equipment Life Characteristics on Missile Test Planning
13. ORNL - Instrum. & Controls Division Annual Progress Rept. - 1 Sept. 1966
14. Eval. Methods & Ways for Increasing the Reliab. of Auto. Control Res.
15. Tri-safe Single Axis Control System - Final Report
16. Self Organizing Control of Aircraft Pitch Rate & Norm. Accel. - Final Rept.
17. Reliab. Pred. & Demo. for Airborne Electronics
18. Applic. of Redundancy in Saturn 5 Guid. & Control System
19. Reliab. Contrib. of the Pilot to a Large Launch Vehicle Control System
20. Power Conditioning Reliability Improvement Through Standby Redundancy and Automatic Failure Detection
21. Electronic Component Vibration Sensitivity
22. The State of the Art - Instrumentation & Controls
23. Failure Rate Compar. Based on Mariner Mars - 1964 Spacecraft Data
24. Reliab. Screening of Electronic Comp.
25. Flight Vehicle Power Systems Reliab. Criteria
26. Methods of Predicting Combined Electronics and Mech System Reliab.
27. System Reliab. Prediction by Function
28. * A Reliab. Model and Anol. for Project Mercury
29. Industrial Electronics Control
30. NASA Control System Research
31. ** Reliability Trend Indicators WS107A-1 Program
32. Martin Co. Reliability Status Report
33. Summary of Titan Vehicle Anomalies

* See Enclosure (1)
** See Enclosure (2)

RESULTS

A review of the above listed sources yielded two samples of system failure rate data. These data are presented in Enclosures (1) and (2).

T.W. Klinefelter
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING

5.2

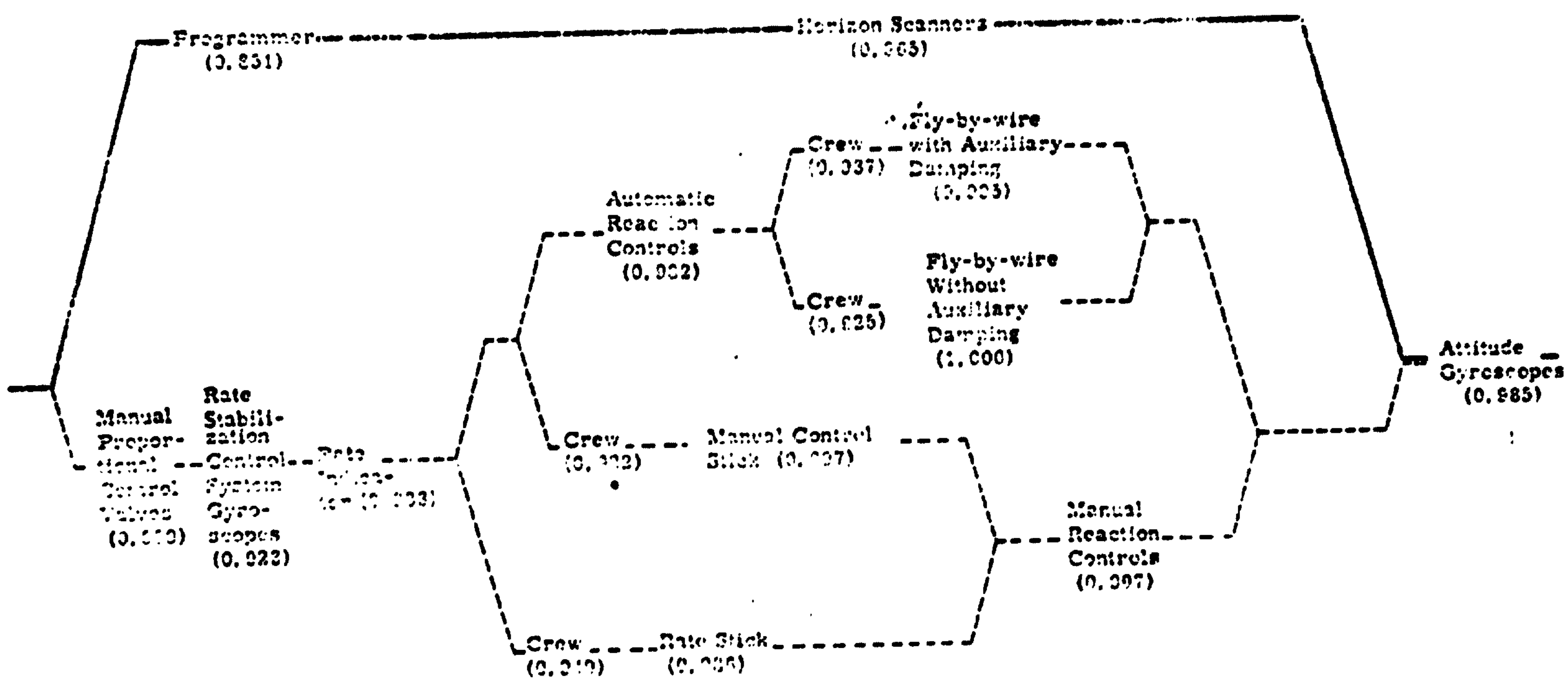

Fig. 3-A ATTITUDE CONTROL SUBSYSTEM-RESET ATTITUDE GYROSCOPES DURING THIRD ORBIT
(Omitting relays, switches, fuses, etc.)

Reliabilities are shown in parentheses. ——— Automatic Mode: Reliability = .809. ----- Additional Crew Back-up: Reliability = 0.152. Total Attitude Control Subsystem Reliability = 0.961.

Based on flight test success, Series E operational systems have the following rank order reliability.

System	One Month Ave (%)	*Present (%)
Airframe	100.0	100.0
Range Safety Command	100.0	100.0
Launcher	100.0	100.0
Re-entry Vehicle	100.0	100.0
Electrical	100.0	100.0
All-Inertial Guidance	100.0	100.0
Pneumatic	100.0	100.0
Hydraulic	85.7	87.5
Flight Control (Square Autopilot)	85.7	87.5
Propulsion	80.6	76.5
Propellant Utilization	62.6	80.5

*8 December 1961

Based on flight test success, Series F operational systems have the following rank order reliability.

System	One Month Ave (%)	*Present (%)
Airframe	100.0	100.0
Range Safety Command	100.0	100.0
Launcher	100.0	100.0
Re-entry Vehicle	100.0	100.0
Electrical	100.0	100.0
All-Inertial Guidance	100.0	100.0
Pneumatic	100.0	100.0
Propulsion	100.0	100.0
Hydraulic	100.0	100.0
Flight Control (Square Autopilot)	100.0	100.0
Propellant Utilization		

*8 December 1961

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5.4

Program Composite Testing

Between 23 October 1961 and 22 November 1961, six missiles were shipped (114D, 32[illegible], 6[illegible], 187, 257, and 277). Between 21 September 1961 and 24 October 1961, twelve missiles were shipped (93D, 123D, 125D, [illegible], [illegible], [illegible], 127, 177, 187, 197, 207 and 227).

The average number of composite tests per missile for the last 20 Series D missiles is 1.35. The average number of composite tests for the last 20 Series E missiles is 1.16. The average number of composite tests per missile for the last 20 Series F missiles is 1.70.

System Failures Per Test During Hot Firings

The following systems have the highest failure rates for Series D missiles. Failure rates indicated are failures divided by total tests.

f/cycle

Ground Support Systems	One Year Ave	One Month Ave	*Present
Other (See page 86)	0.773	0.722	0.724
Launcher	0.622	0.623	0.613
Facilities	0.474	0.493	0.463
Pneumatic Power	0.442	0.413	0.403

*1 November 1961

Airborne Systems	One Year Ave	One Month Ave	*Present
Instrumentation	0.450	0.432	0.437
Airframe	0.101	0.093	0.097
Propellant Utilization	0.104	0.095	0.094
Electrical	0.067	0.022	0.027
Flight Control	0.070	0.072	0.077
Pneumatics	0.073	0.023	0.062
Hydraulics	0.055	0.021	0.021

*1 November 1961

* Based on sample of 58 Series D Atlas Missiles

MEMORANDUM

TO: J. Goldin*

DATE: 12 August 1969
7850:M0250

FROM: R. E. Lavond*

SUBJECT: Trend Data Program

COPIES TO: J. J. Beereboom*, W.M. Bryan*, B. Mandell*, J. H. Ramsthaler*, F. H. Wark*, D. W. Whittlesey*, 7850 Personnel

ENCLOSURES: (1) Reliability TDP Functions
(2) Reliability Comments to Phase I of the Trend Data Implementation Plan (To * only)

As requested, anticipated reliability participation in subject program is presented in Enclosure (1). Comments to the first draft of subject implementation plan are included in Enclosure (2).

R. E. Lavond
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Bryan 8/13/69
CLASSIFYING OFFICER DATE

5.5

Enclosure (1)
7850:M0250

RELIABILITY TREND
DATA PROGRAM FUNCTIONS

Reliability will contribute to the identification of Trend Data Characteristics from those parameters identified, in the Failure Mode Analyses as critical parameters, by Engineering, Quality Assurance, Materials, Stress, Safety, Systems and other contributing disciplines. Selected TDCs will be further identified as to period of surveillance: a) through ground testing only, b) through flight testing.

In cooperation with the above disciplines, Reliability will establish initial limits for TDC identified. Analytical tools to assess and reassess trends and trend limits will be developed and documented, and TDC limits will be provided for input into suitable documentation along with necessary analytical monitoring and surveilling techniques. Instrumentation requirements will also be established, at this time, in cooperation with Measurement personnel.

As testing progresses, Quality Assurance will be responsible for securing, recording, reducing and transmitting results of all TDCs as required by specification, drawing or test plan. Any TDC falling outside established limits will be noted on a separate "TDC" Inspection Report and transmitted within TBD hours of the event per NRP 400 to Program Management, Systems Department Manager, the Reliability Manager and the TDP Manager.

Reliability will act within TBD days to determine, coordinate and report back on corrective action taken. Such actions will usually consist of checking to definitely establish a TDC out of control, checking the control limit for continued suitability, consulting with affected disciplines to scope the problem and finally to choose the most appropriate course of action and initiate corrective action.

RELIABILITY COMMENTS TO PHASE I OF THE TREND DATA PROGRAM IMPLEMENTATION PLAN

I. INTRODUCTION

The scope and purpose of the TDP should be spelled out explicitly in the introduction, such as: "The purpose of the TDP is to identify and monitor selected characteristics of the NNSS and its components as a means of detecting trends which may indicate an adverse effect on the reliability of the NNSS. The monitoring of these characteristics will be conducted through all phases from raw material, processing of parts and assembly, shipping, handling, storage, checkout and operation.

"For the purpose of this program, trend data characteristics "TDCs" will be selected. The TDCs are characteristics of the component or assembly which when analyzed for trends would indicate changes such as deterioration, wear, or changes in critical processes or procedures. Since the changes of interest in this program are those which would indicate adverse changes in reliability, the TDCs can be thought of as reliability indicators. There are two types of TDCs:

"A. A characteristic of an item which can be observed on the same item at succeeding points in time to detect changes in the item, and

"B. The characteristic of a class of items which can be observed on items of the same type at a given point in time (i.e., part-to-part variability).

"It is recognized that many characteristics could fall into both categories; however, the purpose of the trend data program is primarily to observe those characteristics indicated under paragraph A. above, that is, those which vary within one particular component rather than part-to-part variations. It must be noted that the items falling under paragraph B. above are commonly considered to be quality controlled characteristics and as such would not necessarily be included in the TDP program.

"To further clarify this point, it might be pointed out that trend data will include only the most significant characteristics in which changes can indicate something about an item's probability of performing as required. It does not include the large quantities of quality control data which are collected and analyzed for trends in the normal management of a quality control program.

2. **Trend Data Program Objectives**

It is our understanding from the SMPO-C letter that there are basically seven aspects of the TDP program and in that letter Mr. Schroeder spelled out these seven as being primary objectives to the program. They are:

(1) Considerations in design;

(2) Considerations in fabrication;

(3) Considerations in test;

(4) Data collection;

(5) Data retrieval;

(6) Data analysis; and

(7) Feedback to design, fabrication, or test, as applicable.

As indicated in that letter, it was pointed out that items (4) and (5) were adequately covered in the previous AGC proposal; however, the other five items were not covered in enough detail. It is felt the purpose of the present implementation plan is to discuss these requirements and to indicate how each will be satisfied. It is not necessary to spell out in this section the

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responsibility and schedule for each task; however, a brief list of typical tasks, such as failure mode analysis, identification of critical characteristics, assessment of measurement capabilities, etc., should be included and referenced back to Figure 2, the Task Tabulation, included with the preliminary Implementation Plan.

3. Definitions

It is recommended that definitions be moved from Section 4 to Section 3. It is necessary that the various terms be understood before reading this plan. The terms and definitions given are too general and are not explicit enough for this plan.

4. Trend Data Program Phases

This section of the implementation plan appears to be adequate for a first draft. I would not at this moment make any suggestions for changes other than to comment that the language used will have to be changed to remove the familiar tone conveyed in the present draft.

5. Implementation Plan

The general comment on this section which was called Section VI in the draft, is that five requirements have been identified here. These are essentially the five items that came out of our previous working group. It seems imperative that we tie these five items back to the basic seven requirements of the SNPO-C letter so that we can show a definite tie-in between the two and show how we plan to meet their requirements; otherwise there appear to be some gaps between what we are planning to do and what was requested by the Customer.

5.7

It's a little difficult to correlate the five items listed with the seven requirements and to really have a warm feeling that we have covered every item requested. What seems to be required here is that each of the seven items previously mentioned be spelled out in detail so anyone reading this document would understand, at least in a general way, what the intent was, how we are implementing such things as the identification of the initial trend data characteristics for systems, subsystems, etc.

6. **Trend Data Program Features**

In this section, basically we should describe in detail the operation of each organization; that is, how it operates presently within NRO, and how these department's organizations or disciplines will interface with one another so as to accomplish the various tasks (the seven requirements as spelled out by SNPO-C) of the Trend Data Program. It must be shown how design engineering, quality and other disciplines interface with one another, how a component or system is looked at, by whom, who decides what things are critical, how critical parameters are defined, how these are resolved into a final discrete list of critical characteristics to be monitored throughout the program, how these critical characteristics are monitored from conception stage to flight, what data will be collected, how it will be collected, and how it will be controlled, who is responsible for determining the documentation method and how those pieces of data which are not considered critical characteristics will be separated from those that are critical characteristics. Then, it is felt, the customer will be able to understand the AGC-NRO method of implementing this program.

5.10

7. **Figure 1 - Flow Chart**

No comments.

8. **Figure 2 - Task Tabulation**

The column headed "Schedule" should read "Schedule - Days Before PDR", and within the body of the table, remove all "PDR" references. A general suggestion would be that instead of the five items being shown, the seven items stipulated by SNPO-C again be spelled out so that our implementation and compliance with those requirements will be made clear.

Our general concern remains: nowhere have we stated the relationship of this program to the NERVA Program Plan, Reliability Program Plan, Quality Program Plan, and all the other aspects of the existing NERVA Program, which could be impacted by the Trend Data Program. It is necessary somewhere (and probably in the scope of the statement) to indicate exactly what this relationship is: i.e., is the Trend Data Program an extension of the existing NERVA Program, or does it fall within the scope of that program? It would appear desirable to spell out in some detail the responsibilities of, and the responsible individuals on this program, and exactly how this program will be handled from a priority standpoint. It may be necessary to stop NERVA testing because some Trend Data parameter cannot be monitored. How would this impact the overall program? It is suggested that this be spelled out so that the Customer will know exactly what costs are involved in the overall program.

The current reliability commitment is to complete Failure Mode Analyses 30 days prior to PDR.

5.11

J.J. Beereboom, W.M. Bryan, J.L. Dooling, R.V. Evleth, B.Mandell, A.J. Mihanovich, D.E. Price, J.H. Ramsthaler, G.L. Ryland, W.O. Wetmore. W.F. Herwig (AGC-Washington), W.L. Snapp (AGC-Cleveland), CAD Files

ROUTING LIST		
NAME	INITIAL	DATE
Beereboom		
Evleth		
Ryland		
Ramsthaler		5/21
Bryan		
A F Yoder		

26 August 1969
7850:L0252

Mr. D. Gabriel
AEC-NASA Space Nuclear Propulsion Office
U. S. Atomic Energy Commission
Washington, D. C. 20545

Attention: Col. R. S. Decker

Subject: Review of "Confidence Level in System Reliability Estimates"

Reference: (a) SNPO Memo, R. S. Decker to AGC, J. H. Ramsthaler, dtd 18 July 1969, Same Subject

Dear Mr. Gabriel:

A review has been made of the report "Confidence Level in System Reliability Estimates" which you transmitted. The report represents an interesting approach to the problem of confidence interval estimates associated with systems, and supports our current approach of concentrating on developing confidence at the failure mechanism level. The subject method indicated that, contrary to the Lloyd and Lipow "apportionment method", our approach is conservative and that if we assure 90% confidence at the part mechanism level, the overall system confidence level will be considerably higher than 90%.

It is felt, however, that the general application of the results of the report are unnecessarily restricted by the assumptions made concerning normality. The attached enclosure presents some possible suggestions for obviating these restrictions and making the analysis in the report more general. Utilizing these suggestions, it is felt that the same conclusions would be derived.

Very truly yours,

AEROJET-GENERAL CORPORATION

Original Signed By
W. O. Wetmore
Manager
Nuclear Rocket Operations

AJM:bjd

Enclosure: (1) Comments and Suggestions to "Confidence Level in System Reliability Estimates"

cc: Dr. L. Nichols, SNPO-C
Mr M. M. Carness, SNPO-C Res. Rep. at Sacramento
Mr . Horton, WANL
Mr . Wagner, WANL

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CLASSIFICATION CATEGORY
UNCLASSIFIED

Enclosure (1)
7850:L0252

COMMENTS AND SUGGESTIONS TO "CONFIDENCE LEVEL IN SYSTEM RELIABILITY ESTIMATES"

The analysis performed in the subject report was based on several assumptions. These included the following:

1. The distribution of the estimated reliability values for each of the components was normal.

2. The system reliability, estimated as the product of the component reliability values, is also normally distributed.

With reference to assumption 1. above, the distribution of the estimated reliability values for any sample size would probably approach normality only if the true component reliability was approximately 0.50. Since generally components with true reliability values greater than 0.99 are utilized, the distribution of estimated component reliability values is highly skewed. The skewness does, however, decrease with increasing sample size.

Assumption 2. above is not a true general statement. Even if R_1 and R_2 were normally distributed, the product $R_1 \cdot R_2$ is not necessarily normal.

The above assumptions restrict any general conclusions which could be derived. To resolve this, the following suggestions are offered:

1. Consider the use of the Tchebysheff inequality to derive the confidence statements.

   a. Under this approach, the only restrictions imposed on the distribution of R_1 and R_2 is that they have finite means and variance.

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The Tchebysheff inequality states that under these restrictions of finite mean and variance

$$P(|y - \mu| \geq K\sigma) \leq \frac{1}{K^2}$$

where:

$$K > 0$$

this inequality holds for any distribution with finite mean and variance. Use of this inequality permits any value of K to be selected for each component to produce any desired confidence level, $1 - \frac{1}{K^2}$. This obviates the necessity for assuming normality for either of the components. The confidence intervals for R_1 and R_2 would still be $\bar{R}_1 - K\sigma_1$ and $\bar{R}_2 - K\sigma_2$ respectively as indicated in the report.

b. The distribution of R_1 R_2 would also be unrestricted, except for finite mean and variance. The confidence interval for this distribution could be expressed as $\bar{R}_1 \cdot \bar{R}_2 - X\sigma_{12}$, where the confidence level associated with X would be as given as the Tchebysheff inequality.

c. Use the general distribution free formula for σ_{12} rather than the formula used in the report which is only valid for normally distributed variables. The following formula could be used:

$$_{12} = \sqrt{\sigma_1^2 \bar{R}_2^2 + \sigma_2^2 \bar{R}_1^2}$$

d. Follow the same argument as that presented in the report to arrive at very similar conclusions.

2. As an alternate to the Tchebysheff inequality, the Camp-Meidell Inequality could be utilized.

a. Under this approach all distributions would be assumed to be unimodal with finite mean and variance. In addition, it would be necessary to assume that the mode of the distribution is within σ of the mean (i.e., the skewness as measured by (mean-mode)/σ would be less than or equal to 1). This inequality states that

$$P(|y-\mu| \geq X\sigma) \leq \frac{1}{2.25X^2}$$

b. The use of this inequality would result in narrower confidence intervals, which is really of no importance to the argument. Subsequent steps would be identical to those suggested above.

Since it appears that the conclusions reached in the reference report would be unchanged by the incorporation of the above suggestions, the assessment techniques presently planned for use on components in the NERVA Program would be expected to produce conservative results at the system level. As such, the NPRD confidence requirements for reliability assessment would be satisfied.

5.15

MEMORANDUM

TO: R. G. Ackerman

DATE: 23 September 1969
7850:M0285

FROM: A. J. Mihanovich

SUBJECT: Nozzle Tube Thermal Fatigue Test Plan

COPIES TO: J. J. Beereboom, W. M. Bryan, D. Buden, E. V. Krivanec, J. H. Ramsthaler, E. A. Sheridan, L. A. Shurley, F. C. Valls, J. L. Watkins
NTO: W. H. Bushnell

REFERENCE: (a) Technical Directive No. 28, Criteria and Materials Properties Data Book and Design

ENCLOSURE: (1) Statistical Test Plan -- Nozzle Tube Thermal Fatigue Evaluation

The purpose of this memorandum is to formalize verbal agreements reached concerning a test program to determine thermal fatigue properties of the NERVA nozzle tubes.

A proposed statistical test plan is presented in Enclosure (1). The test plan consists of a series of tests-to-failure conducted at various combinations of tube R/t ratio, tube wall temperature, and hold period duration. To comply with customer direction, the plan has been designed to satisfy the requirements specified in Reference (a). In addition, the plan has been designed to permit preliminary analyses based on partial completion of testing and test plan re-direction or modification as a result of the preliminary analyses.

A. J. Mihanovich

A. J. Mihanovich
Reliability
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CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE

5.16

STATISTICAL TEST PLAN

NOZZLE TUBE THERMAL FATIGUE EVALUATION

I. INTRODUCTION

The coolant tubes utilized in the NERVA nozzle consist of U-shaped passages attached to the nozzle wall. The material from which the tubes are fabricated is CRES 347 stainless steel sheets. Since LH_2 flows through the tubes while the external walls of the tubes are exposed to the hot gases flowing through the nozzle, a temperature gradient is established across the tube wall. If the tubes are subjected to thermal cycling while exposed to a sufficiently high temperature gradient, tube rippling, followed by tube buckling, and eventually, tube cracking could occur.

A statistically designed test program has been proposed to evaluate the susceptibility of the current tube design to this thermal fatigue phenomenon. A secondary purpose for the test program is to establish the estimated "critical" R/t curve for CRES 347 stainless steel. This curve theoretically defines, as a function of the tube temperature gradient and tube R/t ratio, the region wherein thermal fatigue can be expected to occur.

II. METHOD OF TESTING

For each test condition, the test item will consist of a bundle of 6 U-tubes mounted on a one-inch thick steel plate. Nozzle temperatures on the exterior of the tubes will be simulated by using a Quartz lamp mounted above the tubes. Bulk flow temperatures within the tubes will be simulated by flowing LH_2 at the appropriate pressures through the tubes.

III. TEST PLAN

An estimated "critical" R/t curve for CRES 347 stainless steel has been postulated. This curve (Figure 1), in conjunction with the dimensional specifications and expected operating regimes of the current design, formed the basis for the

III, Test Plan (cont.)

test plan. As indicated by the curve, it can be expected that increases in R/t ratio and/or tube temperature gradient, ΔT, result in increasing propensity toward tube rippling, buckling, and cracking. Although this curve is theoretical and as such only an imprecise estimator of the true critical R/t curve, it serves a useful purpose as an initial basis for the test plan. The test plan was designed, however, so that it can be readily modified in process if the initial assumptions (location of the curve) proves to be significantly in error.

The primary influencing variables to be evaluated in the testing include:

a. Tube temperature, ΔT, designated as T.
b. Tube R/t ratio, designated as R.
c. Duration of cycle (hold time at specified test condition), designated as H.

Three levels of tube temperature ΔT will be evaluated: 1350°F, 1525°F, and 1700°F. These temperature levels bracket the current design point ΔT of 1400°F.

Three levels of tube R/t ratio will be evaluated: 23.7, 18, and 12. The current design point R/t ratio of 23.7 is included in the group.

In addition, three levels of hold time at specified ΔT will be investigated. These include: 5 min., 15 min., and 30 min. These hold times generally bracket the thrust times anticipated for currently proposed NERVA missions.

The response variables of interest at all of the test points are:

a. Total accumulated cycles to tube buckling.
b. Total accumulated time to tube buckling.
c. Total accumulated cycles to tube cracking.
d. Total accumulated time to tube cracking.

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III, Test Plan (cont.)

The proposed test matrix of 45 tests is presented in Table 1. Each test will consist of repeated cycling at the specified test conditions. Testing of each test unit will be terminated at the point at which a single tube of the bundle of six exhibits cracks or 50 cycles whichever occurs first. The 50 cycle test truncation point has been selected arbitrarily as a reasonable maximum number of cycles to which a test specimen should be exposed.

The test points were selected so that a statistical analysis of the resultant data could be performed. In addition, the test plan has been designed to satisfy the requirements of Technical Directive No. 28, Criteria for Materials Properties Data Book and Design. The pertinent requirements were that:

a. Mean values for each level of a primary variable (in this case - R/t, ΔT and hold time) must be determined from at least 8 values,

b. Estimates of the random variance for the measurement of interest must be determined from at least 15 degrees of freedom.

The first requirement was satisfied by establishing a balanced factorial type experiment. The second requirement was satisfied by providing for replication at six of the test conditions and assuming that the random variation would be homogeneous over all test conditions.

The testing has been designed so that preliminary analyses may be performed following the completion of a portion of the tests. The preliminary analyses will permit decisions to be made as to whether to continue the testing as originally planned, or whether to change the test levels of subsequent tests, or whether all of the replication initially planned is required. In addition, it is planned that the test conditions judged to be most severe should be conducted first. If the cycle lifes observed on these most severe conditions closely approach or exceed the 50 cycle truncation point, then the succeeding less severe tests should be revised since the results of the less severe conditions could be expected to exceed 50 cycles.

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IV. METHOD OF ANALYSIS

The test data resulting from the testing will be initially analyzed by Analysis of Variance techniques. The analysis of variance will permit the statistical evaluation of the effects of the main test variables (tube R/T, ΔT and hold time) and their interactions upon tube life. In addition, an estimate of the random variation in tube life at any test point will be available. The anticipated analysis of variance table with a listing of the sources of variation and associated degrees of freedom is given in Table 2. It should be noted in Table 2 that 18 degrees of freedom are associated with the error or random variation, thus complying with T.D. #28. It is expected that some of the interactions terms may prove to be negligible, and their degrees of freedom may be combined with the error degrees of freedom to provide even more degrees of freedom for the error or random variation.

The time/cycles to buckling (for all six tubes in the bundle) and to cracking (only for the first tube in the bundle to crack) will be recorded at each test condition. The result will be response surfaces relating R/t ratio, ΔT, and hold time plus any significant interactions among these to tube life in terms of either buckling or cracking. The response surface can be used to evaluate the accuracy of the curve presented in Figure 1. In addition, the response surface can be used to estimate nozzle tube reliability at each of the test points. Assuming a mission requirement of ten thrust cycles, the probability of completing ten cycles without failure can be calculated using the test results at each of the test points. For example, based on the test results, an expected life can be estimated at each test point. Assuming cycles to failure are normally distributed and using the random variation to estimate the standard deviation of cycles to failure, the area under the failure distribution to the right of 10 cycles provides an estimate of the reliability of a nozzle tube designed to the specification defined by the test point. This is graphically presented in Figure 2.

Finally, if reliability values are calculated at each of the test points, as described above, a reliability response surface can be defined. This surface would provide estimates of nozzle tube reliability as a function of R/t ratio, tube temperature ΔT, and cycle hold time.

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Table 1

PROPOSED TEST PLAN

Tube Temp. ΔT (°F)	Cycle Hold Time (Min.)	Tube R/t Ratio		
		23.7	18	12
	5	XX	XX	X
1350	15	XX	XX	X
	30	XX	XX	X
	5	XX	XX	X
1525	15	XX	XX	X
	30	XX	XX	X
	5	XX	XX	X
1700	15	XX	XX	X
	30	XX	XX	X

NOTE: Each X in the above table indicates one tube bundle tested to cracking or 50 cycles, whichever occurs first.

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Table 2

ANALYSIS OF VARIANCE TABLE

Source of Variation	Degrees of Freedom
Main Effects	
R/t Ratio, R	2
Tube Temp. ΔT, T	2
Cycle Duration, H	2
Interactions	
R x T	4
R x H	4
T x H	4
R x T x H	8
Random Effects	18
Total	44

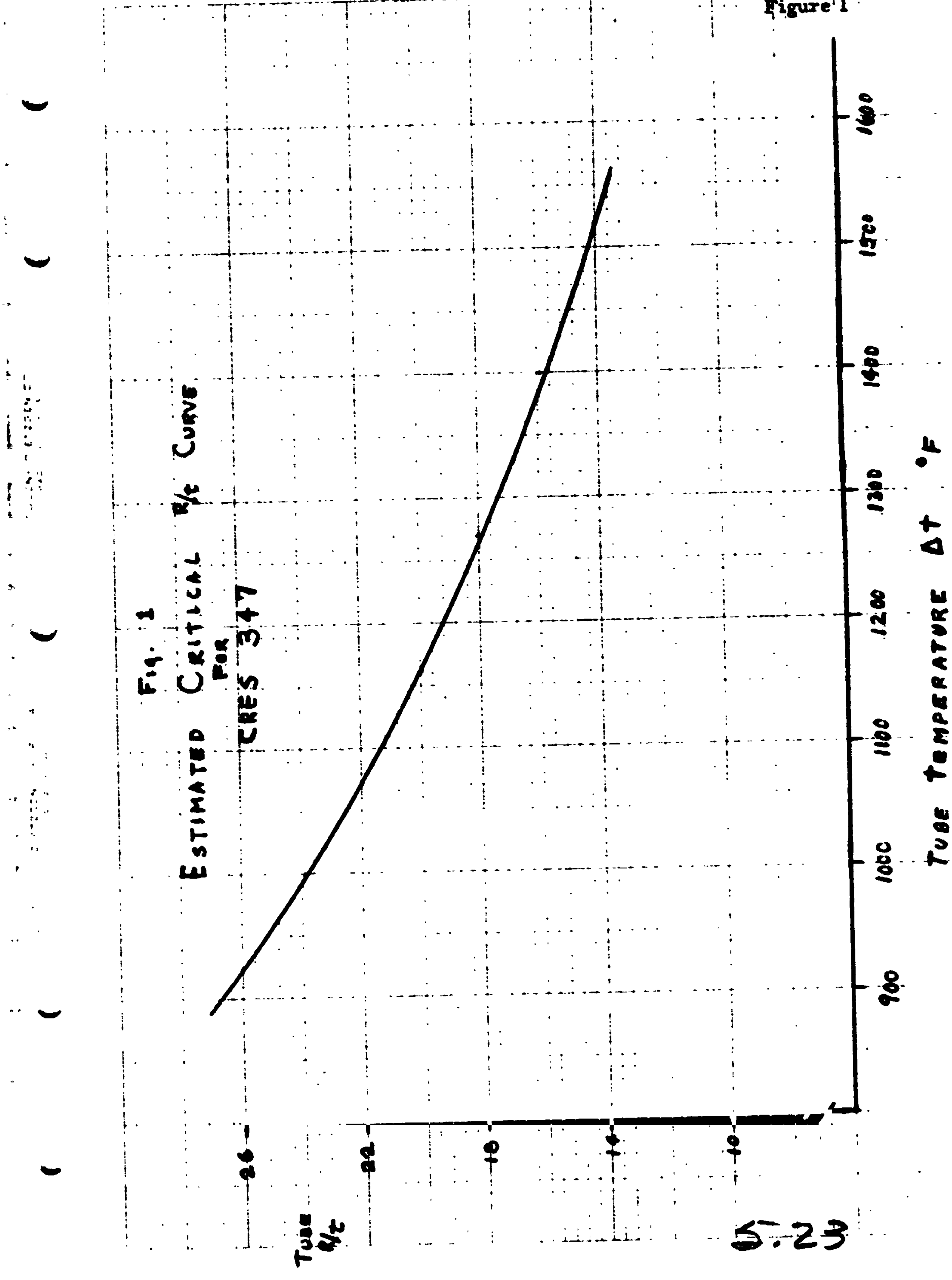


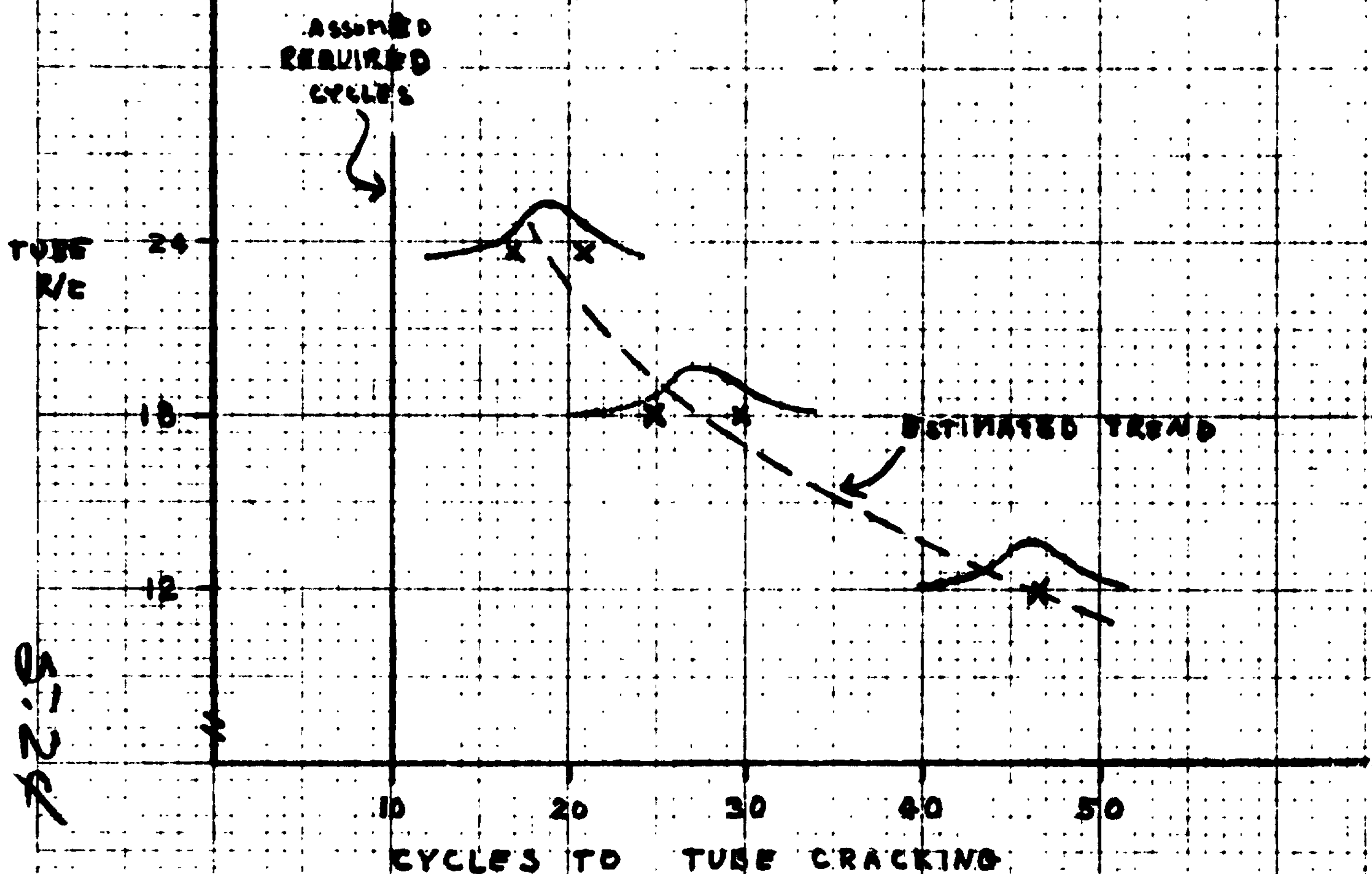
Fig. 1
Estimated Critical R/t Curve
For
CRES 347
Tube Temperature Δt °F
900
1000
1100
1200
1300
1400
1500
1600
Tube R/t
26
22
18
14
10

Enclosure (1)
7850:M0285
Figure 2

FIGURE 2

RELIABILITY ESTIMATION

ASSUMED TEST RESULTS FOR ΔT ≈ 1700°F
AND
30 MIN. HOLD TIME



S:24

MEMORANDUM

TO: L. D. Johnson — DATE: 22 October 1969
7850:M0306

FROM: A. J. Mihanovich

SUBJECT: Statistical Input to General Valve Test Program

COPIES TO: J. J. Beereboom, W. M. Bryan, D. Buden, J. M. Klacking, K. P. Oldenburger, B. Mandell, J. H. Ramsthaler, E. A. Sheridan, A. G. Spears
NTO: W. H. Bushnell

ENCLOSURE: (1) Inputs Submitted for Inclusion in the General Valve Test Program

The attached enclosure formalizes the statistical inputs submitted to Department 7770 for inclusion in the general valve leakage evaluation test program being developed by Department 7770. The inputs include two test plans -- one for preliminary Phase I testing, and a second for more detailed Phase II testing. In addition, general writeups developed to suit the test program outline prepared by Department 7770 are presented. These include sections on Statistical Considerations, Statistical Analysis of Test Data, Determination of Threshold Values and Allowable Limits for NERVA Values, and Integration of Test Results to New Design Criteria.

The variables used in the test plan were defined by Department 7770. In a previous attempt to statistically analyze seal data (the Apollo Bipropellant Valve) additional variables were considered. These variables may have a significant impact on sealing capability and thereby mask the effects of the variables considered in the enclosed test plan. It is suggested that careful consideration be givento the following variables, as well as others, and that each be carefully controlled as constants or variables:

Seal load during cycling as well as during leak check.

Initial and final surface finish.

Temperature of seal retainer and seat.

Compression set of seal and/or closure.

Impact force of seal against seat.

Deflections of shafts or other moving parts under load.

It is recommended that the above factors be considered in the planned revisions of the test program.

A J. Mihanovich

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CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER — DATE

5.25

Enclosure (1)
7850:M0306

II. TEST PROGRAM DEFINITION

A. STATISTICAL CONSIDERATIONS

1. General

In any test program where the effects of a large number of variables are being investigated, a systematic procedure is mandatory to assure meaningful results. In the past, one common experimental approach has been the so-called "one at a time" approach. This kind of experimentation would study the effect of, for example, varying the first variable at some constant level of the second variable. Then the effect of varying the second variable at some constant level of the first variable would be studied. Thus, factors would be varied "one at a time". The results of such an experiment are fragmentary in the sense that one has learned about the effects of the variables only at fixed levels of the other variables. However, there may be, in statistical language, an interaction effect between the two factors within the range of interest, and the "one at a time" procedure does not enable one to detect it. Statistical test planning methodology provides a comprehensive procedure for resolving this problem.

In general, statistical test planning concepts provide a systematic and mathematically sound basis for the following:

a. Specifying test objectives to assure that the purpose of the testing can and will be satisfied,

b. Analyzing the methods of testing to assure that variations extraneous to the testing planned will not confuse the test results,

c. Selecting the test condition so that the effects of the variables under evaluation and their interactions can be estimated, and

d. Defining prior to the start of testing, the methods for analyzing the test results.

As a result, statistical test design principles were utilized to define the general valve test program.

2. List of Variables

The variables of interest in the valve leakage evaluation test program include the following:

a. Velocity of particle contaminants
b. Quantity of contaminants
c. Valve seat angle
d. Seat contact width
e. Contaminant particle size
f. Contamination rate
g. Temperature of medium
h. Contaminant particle hardness
i. Seat/seal material combination

If two levels of each of the above variables were selected for investigation, a total of $2^9 = 512$ tests would be required to test at all of the possible combinations of the nine test variables. Conducting such a volume of test would not only be prohibitive from the cost standpoint, but it would also result in a highly inflexible test program with no opportunity to revise tests scheduled for late in the test program based on initial test results. The proposed test plan has been designed to obviate these problems.

3. Approach and Assumptions

Among the approaches that can be utilized to evaluate the effects of large numbers of variables are:

a. Perform a broad preliminary survey of all of the variables of interest. Analyze the results; then discard the variables concluded to have insignificant effects on the test responses. Conduct a more detailed test

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II. A, Statistical Considerations (cont.)

program of the surviving more important variables. Such an approach would be based on the use of Fractional Factorials, whereby a fraction of the total possible tests are statistically selected for preliminary testing. The tests are selected so that the main variable and interaction effects can be evaluated. These evaluations are then used to plan the subsequent tests in greater detail.

As an example of the magnitude of testing required for the preliminary survey, assume nine variables are to be evaluated. A 1/4 fraction or 128 tests of the 512 tests possible would be required to permit preliminary evaluations of all nine variables and their primary interaction effects.

b. The amount of testing required in approach a. above can be significantly reduced if there is reasonable evidence to indicate that the effects of some of the variables are independent of the test levels of other variables (i.e., they do not interact). Phase I testing would then be a preliminary evaluation of one group of variables, and a second phase of testing would be used to evaluate the second group of variables at selected levels of the Phase I variables.

The approach selected for the valve evaluation is approach b. In the initial Phase I (Table 1) seven variables would be investigated, each at two levels. These are particle velocity, particle quantity, particle size, particle hardness, contamination rate, seal angle, and seal width. The other two variables would be fixed at selected levels. In Phase II (Table 2) the primary design variables (seal angle and seal width) would be evaluated in conjunction with contamination rate at cryogenic temperatures at three seat/seal configurations. The particle velocity, size, quantity, and hardness would be fixed at levels determined from Phase I results.

The critical assumption in this sequential type testing is that the conclusions derived during the initial phases are valid for the other test conditions utilized in the latter phases. For example, the effects of particle hardness, evaluated during Phase I, will be based on testing the hard/hard seat/seal combination. It is assumed that the conclusions concerning the particle hardness at this seat/seal combination will apply to the other seat/seal combinations.

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II.A, Statistical Considerations (cont.)

Additonal assumptions made are as follows:

a. Each test response will be defined by a continuous type variable(s).

b. The random variation will be constant over all test combinations.

c. Since only two levels are utilized for each variable, the responses are essentially linear from one level to the next of each variable.

d. During Phase I testing, a 1/4 fraction, 32, of the $2^7 = 128$ possible tests, is proposed. The reduced testing was achieved by assuming that some of the possible interactions will not occur. These are velocity x size, velocity x rate, velocity x quantity, size x rate, size x quantity, and rate x quantity. It is felt reasonable to assume that these interactions are highly improbable. All other two-way interactions and the main effects of the seven variables are estimable, however.

Wherever feasible, the sequence of testing within a phase will be randomized. This will minimize the effects of extraneous variations (such as day-to-day or test operator differences) which could affect the conclusions.

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V. ADAPTATION OF TEST RESULTS TO NEW DESIGN

A. STATISTICAL ANALYSIS OF TEST DATA

The test plans developed for Phases I and II were designed so that analysis of variance techniques can be utilized to analyze the test results. The analysis of variance is a statistical computational procedure whereby the total variation in a set of data (test results) is divided into meaningful parts. For example, the total variation is divided into variations attributed to changes in level of Variable A, B, C, etc., and changes in levels of A and B in unison (interactions of A and B) etc. These variations due to the main variables and their interactions can then be statistically tested to determine if they are in fact real or could in reality be due merely to normal random variations generally observed in a set of data. This is accomplished by estimating the amount of change in response caused by changing from the low level to the high level of a variable. This change in response is called the "effect" of the particular variable. (For example, the effect of contamination rate is defined as the net change in leakage caused by changing from the low level contamination rate to the high level contamination rate.) This effect of the variable is then compared with the amount of difference in response (leakage) which could be attributed merely to test-to-test variations. If the effect of a variable is significantly greater than the test-to-test variation, then the effect is judged to be real; however, if the effect is within the "range" of the test-to-test variation, then the variable is not considered to have a significant effect upon the response (leakage).

In general, the analysis of variance will provide the following:

1. Estimates of effects on the response of changing levels of each of the variables.

2. Estimates of the effects on the response of interactions of the variables.

3. Statistical tests of significance to determine if these effects are real or could be due merely to random variation.

4. Estimates of the random variation in the data (test-to-test variation due to extraneous causes).

Normally, the random variation is estimated by conducting repeated testing at the same test condition and observing the variability in the results. The standard deviation of this random variation is herein designated as Sw. The testing proposed in Phases I and II does not allow for any repeated testing from which to estimate Sw. However, in analyzing the results of tests with large numbers of variables (such as in Phases I and II), the analysis of variance procedure permits the estimation of the effects of high order interactions, e.g., the interaction among variables A, B, C, E, and F. The usual assumption is that high-order interactions are physically impossible, and that the estimates so labeled are actually estimates of the random variations. For the analysis planned, all third (three factor) and higher order interactions will be used to estimate the random variation.

In addition, based on the above analysis, a mathematical model of the form presented below can be developed:

$$Y = M + K_1 A + K_2 B + - - - + K_j (A \cdot B) + - - - - - - \quad (1)$$

where: Y = response (for example, leakage)

M = overall average response (average observed leakage over all test conditions)

K_i = effects of the variables (these could also be considered as influence coefficients for each of the significant variables and their interactions)

A, B, = levels of the variables, A, B, ----- (-1 would refer to the low level, +1 would refer to the high level of a variable. For example, -1 would refer to the lower velocity and +1 would refer to the higher velocity)

This model can be used to predict the expected response for various combinations of the test variables. Also, for each predicted response at each set of test conditions, the random variation described in para. 4. above and determined from the analysis of variance can be used to establish $\pm$ limits about the predicted response. For example, to predict the response at the low

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levels of variables A, B, and C and high levels of variables D, E, and F, the values -1, -1, -1, +1, +1 would be input into the model (1) above for A, B, C, D, E, and F respectively. The resultant value, Y_N, would be the expected response for this combination of variables. Although Y_N would be the expected response for the specific test combination, the actual response would tend to vary about this value due to random variations.

Assuming the responses are normally distributed and Sw is the standard deviation of the responses developed from the random variation, a distribution of responses about Y_N would result. The proportion of this distribution within the specification limits for the response would give an estimate of the reliability with respect to the specific response at the test levels utilized. This is graphically shown in the following figure.

<u>Development of Reliability Values</u>

The area under the curve to the left of S_1 would provide an estimate of the reliability (probability of not exceeding the specification limit) at the specific test variable combination.

B. DETERMINATION OF THRESHOLD VALUES AND ALLOWABLE LIMITS FOR NERVA VALVES

Using the results of the statistical analysis described above, the effects of the contaminant combinations (quantity, rate, size, hardness, and velocity) upon valve configuration could be studied. The relative capability for each design configuration to withstand various levels of contamination could be estimated. These would establish threshold or allowable contamination limits for each design configuration. The most promising design configuration(s) could

V.B. Determination of Threshold Values and Allowable Limits for NERVA Valves (cont.)

then be selected for further evaluation. In addition for each configuration the estimated reliability values could be compared to required reliability values to determine design acceptability from the reliability standpoint.

C. INTEGRATION OF TEST RESULTS TO NEW DESIGN CRITERIA

The ultimate use of the test results would be to suggest new design criteria. For example, the threshold contamination values could be used to establish control limits on permissible contaminants or would define the filtering requirements. Since the relationships would be established between, for example, seal width and leakage response, the test results would indicate the magnitude of seal width which should be considered in subsequent design optimization. Similar analysis would apply to the seal angle. The effects of the other test variables such as particle velocity and hardness should indicate the design criteria required to control these variables.

Enclosure (1)
7850:M0306

PHASE I TEST PLAN

				VELOCITY							
				V_1 Size				V_2 Size			
				S_1 Rate		S_2 Rate		S_1 Rate		S_2 Rate	
Seal Width	Quantity	Seal Angle	Hardness	R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2
W_1	Q_1	A_1	H_1	X						X	
			H_2				X		X		
		A_2	H_1				X		X		
			H_2	X						X	
	Q_2	A_1	H_1		X						X
			H_2			X		X			
		A_2	H_1			X		X			
			H_2		X						X
W_2	Q_1	A_1	H_1				X		X		
			H_2	X						X	
		A_2	H_1	X						X	
			H_2				X		X		
	Q_2	A_1	H_1			X		X			
			H_2		X						X
		A_2	H_1		X						X
			H_2			X		X			

Table 1

5.34

PHASE II TEST PLAN

SEAT/SEAL CONFIGURATION

Seal Angle	Particle Size	C_1 Seal Width W_1	C_1 Seal Width W_2	C_2 Seal Width W_1	C_2 Seal Width W_2	C_3 Seal Width W_1	C_3 Seal Width W_2
	S_1	X	X	X	X	X	X
A_1	S_2	X	X	X	X	X	X
	S_3	X	X	X	X	X	X
	S_1	X	X	X	X	X	X
A_2	S_2	X	X	X	X	X	X
	S_3	X	X	X	X	X	X
	S_1	X	X	X	X	X	X
A_3	S_2	X	X	X	X	X	X
	S_3	X	X	X	X	X	X

Table 2

5.35

MEMORANDUM

TO: A. J. Gianuzzi

DATE: 29 October 1969
7850:M0316

FROM: A. J. Mihanovich

SUBJECT: Review of Proposed Test Program - Physical Properties, Young's Modulus and Poisson's Ratio

COPIES TO: J. J. Beereboom, W. M. Bryan, D. Buden, C. W. Funk, R. B. Glasscock, J. M. Klacking, B. Mandell, J. H. Ramsthaler, E. A. Sheridan, 7850 Personnel
NTO: W. H. Bushnell

REFERENCE: (a) Memo, A. J. Gianuzzi to I. L. Odgers, dtd 10-9-69, Subject: Physical Properties, Young's Modulus and Poisson's Ratio

ENCLOSURES: (1) Alternate Test Plan I
(2) Alternate Test Plan II

A review has been made of the test program proposed in Reference (a). It is stated in Reference (a) that "It is believed heat-to-heat and within-heat variations in E (Young's modulus) and μ (Poisson's ratio) will be quite small so that a minimum number of specimens will be tested". In addition, it is stated that "These measurements and other statistical studies are expected to indicate typical "three sigma" variabilities . . . .".

The test plan, as presented in Table I of Reference (a), does not permit an estimation of within-heat variations and only a cursory statistical analysis can be performed to estimate the heat-to-heat variations, the effects of the anisotropy and the effects of the heat treatment.

A more comprehensive statistical analysis could be performed if the proposed testing is modified as presented in Enclosure (1) or (2). In Enclosure (1), Alternate Test Plan I is presented. Under this test program, a total of 18 specimens from three heats would be tested (as opposed to 16 specimens from four heats in the Reference (a) test program. Alternate Test Plan II, Enclosure (2), provides for testing 24 specimens from four heats. Both test plans would permit a statistical analysis to be performed to estimate the effects of heat treatment and anisotropy. In addition, estimates of heat-to-heat and within-heat variations would be provided. If such information is desirable, Test Plan II would provide a better estimate of the heat-to-heat variation than Test Plan I since four heats are sampled rather than three.

If a statistical analysis of these variables is desired, it is suggested that consideration be given to modifying the testing currently planned to conform to plans such as those presented in Enclosures (1) and (2).

A. J. Mihanovich

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Reliability
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CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE 10/29/69

5.36

Enclosure (1)
7850:M0316

ALTERNATE TEST PLAN I

	Orientation					
	Tangential		Radial		Axial	
Heat/Heat Treatment	A	B	A	B	A	B
1	X	X	X	X	X	X
2	X	X	X	X	X	X
3	X	X	X	X	X	X

5.37

Enclosure (2)
7850:M0316

ALTERNATE TEST PLAN II

	Orientation					
	Tangential		Radial		Axial	
Heat/Heat Treatment	A	B	A	B	A	B
1	X	X	X	X	X	X
2	X	X	X	X	X	X
3	X	X	X	X	X	X
4	X	X	X	X	X	X

5.38

MEMORANDUM

TO: J. L. Watkins

DATE: 12 November 1969
7850:M0335

FROM: A. J. Mihanovich

SUBJECT: Statistical Analysis of CRES 347 Forging Data

COPIES TO: J. J. Beereboom, H. Benenson, W. M. Bryan, D. Buden, N. A. Coronado, W. I. Emmons, C. W. Funk, R. B. Glasscock, J. M. Klacking, C. K. Leeper, B. Mandell, I. L. Odgers, J. H. Ramsthaler, E. A. Sheridan, L. A. Shurley, H. W. Spaletta, S. A. Varga, 7850 Personnel
NTO: W. H. Bushnell

REFERENCE: (a) Memo 7850:M0282, dtd 19 Sept. 69, A. J. Mihanovich to J. L. Watkins, Subject: Preliminary Analysis of CRES 347 Forging Data

ENCLOSURES:
(1) Tensile Specimens, S/N 27; Circumferential, Axial and Joint Orientations, Yield Strength (KSI)
(2) Tensile Specimens, S/N 33; Circumferential, Axial and Joint Orientations, Yield Strength (KSI)
(3) Tensile Specimens, S/N 21; Circumferential, Axial and Joint Orientations, Yield Strength (KSI)
(4) Tensile Specimens, S/N 27; Circumferential, Axial and Joint Orientations, Percent Elongation
(5) Tensile Specimens, S/N 33; Circumferential, Axial and Joint Orientations, Percent Elongation
(6) Tensile Specimens, S/N 21; Circumferential, Axial and Joint Orientations, Percent Elongation
(7) Statistical Analysis of Individual Forgings, Yield Strength (KSI)
(8) Statistical Analysis of Individual Forgings, Percent Elongation

Introduction

A series of mechanical properties tests have been conducted on tensile specimens resulting from the sectioning of three nozzles forged from CRES 347. A statistical analysis has been performed on the results of these tests. The mechanical properties analyzed include yield strength and percent elongation. The purpose of the analysis was an attempt to develop 99% probability at 95% confidence level (99/95) values for these properties to provide initial design data for CRES 347.

Data was available from three forgings - S/N 21, S/N 27, and S/N 33. It is understood that S/N 27 and S/N 33 were supplied by one vendor while S/N 21 was supplied by a second vendor. The data analyzed is presented in Enclosures (1) through (6). The results of a statistical analysis performed on a portion of this data was presented in Reference (a). This report is a brief presentation of the results to date. A final report of these results and the results of additional analyses planned will be presented at a later date.

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Method of Analysis

The method of analysis used is described in Reference (a). The basic steps followed were:

a. For each sample of data at each temperature level at each orientation for each forging, the data was tested for normality. This was accomplished by plotting the cumulative distribution of the data on probability paper and observing whether that data was approximately linear. In those cases where the data was judged non-linear, a logarithmic transformation was used to normalize the data.

b. Means and variances were calculated for each sample of data.

c. Test results at a common temperature, common orientation, and from a common vendor were compared to determine if the within-forging variations (S_w^2) were statistically similar (homogeneous). In those cases where the S_w^2 were not statistically different, the results of the two forgings were combined (pooled).

d. 99/95 values were calculated for all samples. These values are designated as $\bar{X}$-KS,

where: $\bar{X}$ = mean of the sample of data,

K = tolerance factor associated with 99% probabilities and 95% confidence, and

S = standard deviation of the data sample.

Results of the Analysis

The results of the yield strength analyses are presented in Enclosure (7). The results of the analysis of the individual samples are presented on pages 1 and 2 of Enclosure (7). Since these analyses consider only the results at each individual temperature, at each individual orientation, at each individual forging, the 99/95 ($\bar{X}$-KS) values presented reflect only within-forging variations. On page 3 of Enclosure (7) are presented the results where combining (pooling) of separate forgings was permissible. In these cases the standard deviations presented (S_C) reflect the combined within-forging and between-forging variations, and the 99/95 limits ($\bar{X}$-KS_C), consequently, allow for both of these sources of variation.

Similar results are presented for percent elongation in Enclosure (8). The individual analyses are presented on pages 1 and 2 and the combined analyses on page 3 of Enclosure (8).

In both Enclosures (7) and (8), results derived by utilizing the logarithmic transformations of the data are indicated by asterisks.

For design purposes, it would be desirable to have minimum design allowables (99/95 limits) which reflect both sources of variation - within-forging and among-forgings. As indicated on page 3 of Enclosure (7), reasonable 99/95 limits for

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yield strength are available only at -100°F for the circumferential and axial orientations, and at room temperature and 600°F for the axial orientations. In all other cases, either the within-forging variations were non-homogeneous and this precluded the statistical combination of forgings, or there were such great differences among the two forgings that the combined forging results produced nonsensical 99/95 values.

For percent elongation, as indicated on page 3 of Enclosure (8), a potentially reasonable 99/95 value, considering both sources of variation, was available only at room temperature for the axial orientation. In all the other cases the forgings were either non-combinable or were so different as to produce nonsensical results when combined.

Conclusions

From the results of the analysis, it appears that in all but a few cases, no general standards considering both among and within-forging variations have been developed. Among the causes for these could be:

a. Further discussions with mater ls personnel indicate that the two forgings (S/N 27 and S/N 33) although from the same vendor, were of different design configurations,

b. It appears reasonable that different forging processes were utilized to develop the two forgings,

c. The within-forging variations and among-forging variations could have been affected by differing locations of the tensile specimens, and/or

d. The test laboratory did not exercise adequate control of extraneous sources of variations during tensile specimens testing.

Efforts are being currently undertaken to evaluate item c. above. This will be accomplished by studying each tensile specimen test result with reference to its corresponding location in the nozzle ring.

With respect to the overall results, several courses of action are available. These include the following:

a. Fabricate additional forgings by the same vendor with a common highly controlled forging process. Section these forgings to produce, hopefully, more consistent test results.

b. Establish a procedure whereby each forging is analyzed and rejected or accepted on its own merits. This would obviate the forging-to-forging variation problem. This would necessitate studying and determining the correlations between the tensile bars received during receiving inspection and the high stress regions of the forging. Data, of this nature, currently available, will be analyzed to determine if this approach is feasible.

CLASSIFICATION CATEGORY
UNCLASSIFIED
[illegible] 11/19/[illegible]
CLASSIFYING OFFICER DATE

A. J. Mihanovich

5.41

A. J. Mihanovich
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

Enclosure (1)
7850:M0335

TENSILE SPECIMENS, S/N 27
CIRCUMFERENTIAL ORIENTATION
YIELD STRENGTH (KSI)

[illegible]	-100°F	RT	600°F	1200°F	1400°F	1600°F
30.1	36.4	34.4	21.4	16.9	18.8	11.7
[illegible]	35.4	32.3	24.4	17.6	15.9	11.7
[illegible]	35.4	30.8	22.0	17.6	20.4	12.6
[illegible]	37.1	34.0	20.8	17.8	18.1	[illegible]
35.4	36.2	33.7	21.4	19.6	18.1	
[illegible]	36.2	32.2	20.9	18.8		
[illegible]	37.1	34.2	20.0	20.5		
[illegible]	36.6	30.6	24.4	22.7		
27.1	31.9	32.7	25.5	18.9		
26.8	34.0	34.0	28.1	18.3		
27.6	34.6	34.6	24.7			
28.5	35.2	35.0	33.8			
26.8		32.7				
26.8		33.5				
29.2		34.8				

TENSILE SPECIMENS, S/N 27

AXIAL ORIENTATION
YIELD STRENGTH (KSI)

[illegible]	-100°F X	RT	600°F	1200°F	1400°F	1600°F
33.8	34.2	30.7	20.2	19.5		
31.0	33.0	31.1	20.2	19.8		
33.4	34.2	30.3	21.5	18.6		
[illegible]	33.5	30.9	20.8	17.8		
33.5	34.6	30.7	21.8	17.0		
32.8	33.2	29.7	21.3	17.6		
34.3	34.0	31.7	22.3	17.4		
29.1	34.5	29.5	21.6	17.5		
36.8	33.1	29.1	21.7	19.4		
33.2	34.2	29.3	20.6	17.3		
32.3	34.2	30.5	21.0	17.6		
37.3	32.0		23.4	16.9		

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Enclosure (1)
7850:M0335

TENSILE SPECIMENS, S/N 27
JOINT ORIENTATION
YIELD STRENGTH (KSI)

[illegible]	-110°F	RT	600°F	1200°F	1400°F	1600°F
		31.5				
		32.0				
		32.5				
		33.2				
		32.4				
		32.9				
		33.1				
		32.2				
		31.4				
		31.1				
		32.7				
		33.2				

TENSILE SPECIMENS, S/N 33
CIRCUMFERENTIAL ORIENTATION
YIELD STRENGTH (KSI)

[illegible]	[illegible]	RT	[illegible]	[illegible]	[illegible]	[illegible]
31.7	[illegible]	30.1	20.2	[illegible]		
[illegible]	[illegible]	[illegible]	21.1	[illegible]		
[illegible]	[illegible]	[illegible]	22.6	[illegible]		
[illegible]	35.4	[illegible]	21.1	19.3		
[illegible]	[illegible]	[illegible]	20.2	[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]	[illegible]	21.4	[illegible]		
[illegible]	[illegible]	[illegible]	19.7	[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	18.2		
[illegible]	[illegible]	[illegible]	[illegible]	19.1		
[illegible]	[illegible]	[illegible]	20.7	[illegible]		
	[illegible]	[illegible]	22.3	[illegible]		

[illegible]

TENSILE SPECIMENS, S/N 33
AXIAL ORIENTATION
YIELD STRENGTH (KSI)

[illegible]	-110°F	RT	600°F	1200°F	1400°F	1600°F
[illegible]	36.4	20.0	22.9	18.9		
[illegible]	[illegible]	20.6	21.5	19.3		
[illegible]	34.7	29.9	21.0	19.4		
[illegible]	36.2	29.5	20.9	20.6		
[illegible]	33.7	[illegible]	21.1	19.1		
[illegible]	35.6	[illegible]	21.0	19.9		
[illegible]	32.8	[illegible]	21.7	18.7		
[illegible]	34.0	29.5	22.3	20.3		
[illegible]	35.4	29.2	21.4	20.5		
[illegible]	32.0	28.7	21.0	18.9		
[illegible]	35.2	29.1	22.0	19.3		
	35.8	29.7	21.8	19.0		

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TENSILE SPECIMENS, S/N 33
JOINT ORIENTATION
YIELD STRENGTH (KSI)

[illegible]	100°F	RT	600°F	1200°F	1400°F	[illegible]
		29.7				
		29.5				
		26.8				
		[illegible]				
		[illegible]				
		[illegible]				
		[illegible]				
		30.1				
		33.4				
		30.7				
		29.2				
		28.9				

5.47

TENSILE SPECIMENS, S/N 21
CIRCUMFERENTIAL ORIENTATION
YIELD STRENGTH (KSI)

-320°F	-100°F	RT	600°F	1200°F	1400°F	1600°F
[illegible]	32.8	35.4	26.5	22.2		
37.0	32.8	36.0	28.3	23.0		
3?.7	37.1	34.8	27.1	24.0		
[illegible]	33.1	35.7	27.8	23.3		
37.3	33.3	34.8	26.8	23.0		
36.1	30.1	36.2	27.7	23.3		
33.5	29.8	35.4	30.2	23.2		
35.7	32.1	36.4	26.8	22.0		
37.6	35.2	36.4	27.1	22.5		
40.4	32.6	36.8	27.0	21.3		
37.9	34.8	35.4	26.7	22.9		
[illegible]	34.0	38.7	26.3	21.5		

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TENSILE SPECIMENS, S/N 21
AXIAL ORIENTATION
YIELD STRENGTH (KSI)

-320°F	-100°F	RT	600°F	1000°F	1400°F	[illegible]
44.1	34.1	37.2	30.7	24.5		
[illegible]	34.6	38.7	29.2	24.7		
[illegible]	[illegible]	37.7	32.2	24.1		
[illegible]	[illegible]	37.1	29.7	24.3		
[illegible]	[illegible]	37.3	29.9	23.5		
[illegible]	[illegible]	37.7	29.6	23.4		
35.6	34.6	38.6	27.9	22.3		
38.1	[illegible]	38.9	27.2	22.1		
39.1	32.5	37.2	28.5	23.3		
[illegible]	34.1	37.9	27.4	23.3		
36.0	[illegible]	38.0	28.1	23.3		
36.4	[illegible]	36.8	27.5	22.7		

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[redacted]

TENSILE SPECIMENS, S/N 21
JOINT ORIENTATION
YIELD STRENGTH (KSI)

-320°F	-100°F	RT	600°F	1200°F	1400°F	1600°F
		34.9				
		35.4				
		33.1				
		31.8				
		33.9				
		33.8				
		33.2				
		34.0				
		32.5				
		32.6				
		32.7				
		33.5				

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TENSILE SPECIMENS, S/N 27
CIRCUMFERENTIAL ORIENTATION
PERCENT ELONGATION

-320°F	-100°F	RT	600°F	1200°F	1400°F	[illegible]
38	52	54	32	33	54	84
43	53	55	35	35	54	88
43	52	55	35	35	57	90
44	54	56	36	37	58	94
44	54	56	36	38	59	
44	54	57	36	38		
45	54	57	36	38		
45	54	58	37	39		
45	54	58	37	40		
45	54	60	37	40		
45	55	60	38			
45	55	60	38			
45		60				
46		60				
46		60				

TENSILE SPECIMENS, S/N 27
AXIAL ORIENTATION
PERCENT ELONGATION

-320°F	-100°F	RT	600°F	1200°F	1400°F	1600°F
45	53	58	36	40		
50	54	59	36	40		
50	54	60	36	40		
50	54	60	37	40		
50	54	60	37	41		
50	54	63	37	41		
50	55	63	37	41		
51	55	65	37	42		
51	55	65	37	42		
52	55	65	37	42		
52	55	65	37	42		
52	55		38	42		

5.52

TENSILE SPECIMENS, S/N 27
JOINT ORIENTATION
PERCENT ELONGATION

[illegible]°F	-100°F	RT	600°F	1200°F	1400°	1600°F
		60				
		63				
		63				
		63				
		63				
		63				
		64				
		64				
		64				
		64				
		64				
		65				

5.53

TENSILE SPECIMENS, S/N 33
CIRCUMFERENTIAL ORIENTATION
PERCENT ELONGATION

-320°F	-100°F	RT	600°F	1200°F	1400°F	1600°F
43	54	61	36	37		
41	55	62	36	38		
47	55	62	36	38		
47	55	62	37	38		
47	55	62	37	38		
48	55	63	37	38		
48	56	63	37	39		
48	57	63	37	39		
49	57	63	37	40		
50	57	63	37	40		
50	58	65	37	40		
	60	65	37	40		

TENSILE SPECIMENS, S/N 33
AXIAL ORIENTATION
PERCENT ELONGATION

-320°F	-100°F	RT	600°F	1200°F	1400°F	160
[illegible]	50	60	35	34		
[illegible]	53	61	35	34		
46	54	62	35	36		
46	55	62	35	37		
47	55	63	35	37		
47	56	63	36	37		
47	56	63	36	37		
47	56	64	36	37		
48	56	64	36	38		
48	56	65	36	38		
48	57	65	36	39		
	58	66	36	40		

5.55

TENSILE SPECIMENS, S/N 33
JOINT ORIENTATION
PERCENT ELONGATION

[illegible]	-100°F	RT	600°F	1200°F	[illegible]	[illegible]
		54				
		56				
		58				
		58				
		58				
		58				
		58				
		59				
		59				
		59				
		59				
		60				

5.56

TENSILE SPECIMENS, S/N 21
CIRCUMFERENTIAL ORIENTATION
PERCENT ELONGATION

[illegible]	-100°F	RT	600°F	1200°F	1400°F	1600°F
31	40	50	26	33		
33	40	51	30	34		
33	41	51	31	36		
35	41	53	31	36		
35	42	53	31	37		
35	42	54	31	37		
35	43	54	31	37		
35	43	55	32	38		
36	43	56	32	38		
37	43	57	32	38		
37	44	57	33	38		
37	45	58	33	40		

5.57

TENSILE SPECIMENS, S/N 21
AXIAL ORIENTATION
PERCENT ELONGATION

[illegible]°F	-100°F	RT	[illegible]°F	1200°F	1400°F	[illegible]
38	43	51	28	35		
[illegible]	43	53	30	35		
39	44	53	30	36		
3[illegible]	44	54	30	36		
40	44	54	30	37		
40	45	54	31	37		
40	45	55	31	37		
[illegible]	45	55	31	38		
[illegible]	45	55	31	38		
[illegible]	46	55	31	38		
41	46	56	31	38		
[illegible]	46	57	32	39		

JOINT ORIENTATION

PERCENT ELONGATION

[illegible]°F	-100°F	RT	600°F	1200°F	1400°F	[illegible]°F
		45				
		50				
		5[illegible]				
		52				
		52				
		53				
		54				
		54				
		54				
		55				
		56				
		57				

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STATISTICAL ANALYSIS OF INDIVIDUAL FORGINGS
YIELD STRENGTH (KSI)

Temp		I	C	A	I	C	C	I	S	A
-320°F	n		12	12		15	12		11	11
	$\bar{x}$		36.717	37.100		27.033	32.717		31.918	31.445
	s^2		3.007	11.456		5.277	4.287		4.711	6.131
	s		1.734	3.374		2.302	2.071		2.170	[illegible]
	$\bar{x}$-KS		30.22	24.982		20.920	24.957		22.557	[illegible]
-100°F	n		12	12**		12**	12**		12	12**
	$\bar{x}$		33.142	34.3318		35.47497	33.45964		34.600	34.3348
	s^2		4.132	1.00312		1.00185	1.001004		1.051	1.06312
	s		2.033	2.78710		1.04388	1.032177		1.025	2.78710
	$\bar{x}$-KS		25.524	28.4003		30.20589	29.71573		30.757	29.30614
RT	n	12	12	12	12	15**	11	12**	12	12
	$\bar{x}$	33.533	36.000	37.758	32.350	33.2785	30.318	29.7051	29.917	29.325
	s^2	1.077	1.122	0.467	0.526	1.00179	0.676	1.02967	0.782	0.335
	s	1.038	1.057	0.646	0.726	1.04321	0.822	1.11579	0.884	0.579
	$\bar{x}$-KS	29.644	32.032	35.191	29.630	28.67	27.152	26.1225	26.505	27.655
600°F	n		12**	12**		12**	12		12	12
	$\bar{x}$		27.33998	28.13019		23.68701	21.367		20.775	21.550
	s^2		1.00143	1.00373		1.023156	0.532		0.748	0.385
	s		1.03854	1.05359		1.163347	0.912		0.865	0.620
	$\bar{x}$-KS		23.7213	23.708316		13.416867	17.960		17.734	19.227
1200°F	n		12	12		10	12		12**	12**
	$\bar{x}$		22.683	23.542		11.490	17.933		19.11038	[illegible]
	s^2		0.642	0.526		2.885	1.082		1.00107	1.0611
	s		0.801	0.725		1.699	1.040		[illegible]	[illegible]
	$\bar{x}$-KS		19.682	20.825		12.126	14.036		16.91127	17.16246

** [illegible] TRANSFORMATION

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STATISTICAL ANALYSIS OF INDIVIDUAL FORGINGS
YIELD STRENGTH (KSI)

TEMP		S/N 21 I	S/N 21 C	S/N 21 A	S/N 27 I	S/N 27 C	S/N 27 A	S/N 23 I	S/N 23 C	S/N 23 A
1400°F	n					5				
	$\bar{x}$					17.240				
	s^2					2.623				
	s					1.620				
	$\bar{x}$ - KS					7.960				
1600°F	n					4				
	$\bar{x}$					12.225				
	s^2					0.383				
	s					0.618				
	$\bar{x}$ - KS					7.873				

STATISTICAL ANALYSIS OF COMBINED FORGINGS
S/N 27 AND S/N 33
YIELD STRENGTH (KSI)

TEMP		J	C	A
-320°F	n		26	23
	$\bar{x}_c$		30.2538	30.6739
	S_c		2.77	3.72
	n_c		6	3
	$\bar{x}_c - KS_c$		13.204	-8.546
-100°F	n		24	24
	$\bar{x}_c$		35.0542	34.0167
	S_c		1.38	1.43
	n_c		14	10
	$\bar{x}_c - KS_c$		30.104	28.327
Room Temp	n	24	** 27	23
	$\bar{x}_c$	31.0333	31.6836	30.0609
	S_c	8.01	2.97364	0.76
	n_c	2	2	14
	$\bar{x}_c - KS_c$	-43.527	1.304	27.341
[illegible]00°F	n			24
	$\bar{x}_c$			21.4583
	S_c			0.76
	n_c			23
	$\bar{x}_c - S_c$			19.018

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** LOG TRANSFORMATION

STATISTICAL ANALYSIS OF INDIVIDUAL FORGINGS
PERCENT ELONGATION

TEMP		5/11 61			5/11 [illegible]			5/11 57		
		I	C	A	I	C	A	I	C	A
-320°F	n		12	12		** 15	12		11	11
	$\bar{x}$		35.00	37.75		44.15755	5[illegible].5		47.636	46.909
	s^2		4.909	0.75		1.002133	1.3636		3.6545	0.6[illegible]7
	s		2.2156	0.866		1.047242	1.1677		1.9117	0.[illegible]
	$\bar{x}$ - KS		26.67815	36.5051		37.53538	46.1[illegible]		40.27213	46.[illegible]2
-100°F	n		12	12		12	12		** 12	** 12
	$\bar{x}$		42.25	44.667		53.667	54.417		56.14288	55.10923
	s^2		2.3864	1.1515		1.1515	0.44697		1.00089	1.001495
	s		1.5448	1.0731		1.0731	0.66856		1.030279	1.0[illegible]9
	$\bar{x}$ - KS		36.46163	40.64[illegible]		47.64609	51.91191		50.2056	47.[illegible]7
RT	n	12	12	12	12	15	11	12	12	12
	$\bar{x}$	52.833	54.083	54.333	63.333	57.732	62.091	58.0	62.833	63.167
	s^2	9.7879	6.4106	2.4242	1.5152	4.79095	7.4909	2.5455	1.4242	3.0606
	s	3.1286	2.6097	1.557	1.2309	2.1865	2.73695	1.5954	1.1934	1.7495
	$\bar{x}$ - KS	41.11014	44.30445	48.41892	58.72082	50.83652	51.54827	52.02204	58.36133	56.6116 2
600°F	n		** 12	12.		** 12	12		12	12
	$\bar{x}$		31.02986	30.5		36.048635	36.933		36.75	35.583
	s^2		1.003712	1.00.		1.002141	0.3333		0.2045	0.2652
	s		1.064389	1.00		1.047335	0.5773		0.4523	0.5149
	$\bar{x}$ - KS		24.56074	26.753		30.31292	34.61386		35.15523	33.65367
1200°F	n		12	12		10	12		12	12
	$\bar{x}$		37.0	37.0		37.3	41.083		38.75	37.0
	s^2		2.9091	1.6364		5.3444	0.8106		1.1136	3.0909
	s		1.7056	1.2792		2.3118	0.9003		1.0553	1.7581
	$\bar{x}$ - KS		30.63412	32.20614		28.01672	37.7096		34.74572	30.4124

5.63

* [illegible]

STATISTICAL ANALYSIS OF INDIVIDUAL FORGINGS
PERCENT ELONGATION

TEMP		S/N 21				S/N 27				S/N 3[illegible]		
		I	C	A		I	C	A		I	C	A
1400°F	n						5					
	$\bar{x}$						56.4					
	s^2						5.30					
	s						2.3022					
	$\bar{x}$ - KS						43.1831					
1600°F	n						4					
	$\bar{x}$						89.0					
	s^2						17.3333					
	s						4.1633					
	$\bar{x}$ - KS						59.68204					

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STATISTICAL ANALYSIS OF COMBINED FORGINGS
S/N 27 AND S/N 33
PERCENT ELONGATION

TEMP		J	C	A
-320°F	n		26	23
	$\bar{x}_c$		45.4538	48.7826
	S_c		2.0526	2.72024
	n_a		3	2
	$\bar{x}$ - KS_c		13.43971	-52.122
-100°F	n		** 24	
	$\bar{x}_c$		54.88609	
	S_c		1.04108	
	n_a		3	
	$\bar{x}$ - KS_c		35.88775	
RT	n	24		** 23
	$\bar{x}_c$	60.6667		61.69359
	S_c	4.01041		1.058119
	n_a	2		22
	$\bar{x}$ - KS_c	-44.09544		51.3949
600	n			24
	$\bar{x}_c$			36.2083
	S_c			1.0274
	n_a			2
	$\bar{x}$ - KS_c			-1.90208

5.65

** LOG TRANSFORMATION

M E M O R A N D U M

TO: W. E. Stevens DATE: 17 November 1969
7850:M0336

FROM: J. H. Ramsthaler

SUBJECT: Full Flow Reference Engine - Proposed Revision of SSCSS and Pulse Cooldown System

DISTRIBUTION: J. J. Beereboom, D. Buden, A. D. Cornell, V.M.H. Chang, J. D. Hart, J. W. Hooghton, L. D. Johnson, J. M. Klacking, E. V. Krivanec, C. F. Leyse, B. Mandell, C. K. Leeper, F. L. Openshaw, E. A. Sheridan, S. A. Varga, Section 7850 Personnel

REFERENCE: (a) Memo 7840:M0241, J. M. Klacking to Distribution, dated 4 November 1969, Subject: Full Flow Schematic

ENCLOSURE: (1) Safety and Reliability Analysis of Reference and Proposed Cooldown/SSCSS Systems

Per the request of Reference (a) a suggested improvement from standpoint of safety and reliability is submitted for the Structural Support Coolant Subsystem (SSCSS) and Cooldown System. The schematic for the "Proposed" system, description of operating sequence, safety evaluation and a reliability analysis are presented in Enclosure (1).

Principally the "Proposed" system eliminates the three-way SSCV's for two-way SSCV's, reduces the number block valves, reduces the number of valves requiring analog control, and adds orificed lines to assure coolant flow regardless of valve positions. The safety analysis resulted in better than a 50% reduction (22 vs 10) in component malfunction possibilities having a direct and immediate effect on system safety. The reliability analysis for a single thrusting cycle and an 83-pulse-cooldown cycle resulted in an estimated reliability of .975 for the "Reference" and .989 for the "Proposed" SSCSS and Cooldown supply systems. This constitutes better than a 50% reduction in failure rate (from 0.025 to 0.011). Based on these results, it is recommended that the proposed SSCS and pulse cooldown system configurations be considered for immediate incorporation into the baseline Reference engine configuration.

J. H. Ramsthaler, Manager
Reliability & Safety Analysis Section
Nuclear Rocket Operations

APPROVED:

J. J. Beereboom, Manager
Systems Department
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED

CLASSIFIER CHECK DATE

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SAFETY AND RELIABILITY ANALYSIS OF REFERENCE AND PROPOSED COOLDOWN/SSCSS SYSTEM

1.0 INTRODUCTION

The coolant supply and control networks for the Structural Support Coolant Subsystem (SSCSS) and for the pulse cooldown system as currently defined for the Reference Full Flow Engine are illustrated in Figure 1. The valves for the control and distribution of the structural support coolant consist of two (2) three-way control valves (SSCV) and four (4) block valves (SSBV). The three-way SSCV's are assumed not to have the capability of blocking all stem or bypass flow but, from full open to full closed, only vary the proportion of these two output flows. Because of the difficulties of controlling three-way valves in active redundancy, the sub-system is to be operated in a standby redundancy mode. The valves for the pulse cooldown operations, in addition to those in the SSCSS which are utilized, consist of two (2) redundant control valves (CSCV) and one (1) checkvalve (CSKV).

A revised supply and control network for the SSCSS and for the pulse cooldown system is proposed for incorporation in the Full Flow Engine. The revised supply and control network, illustrated in Figure 2, is proposed partially as a system simplification but more important for improved system safety and reliability. In the SSCSS the three-way SSCV's are replaced with two-way valves, the number of block valves are reduced from four to three, an orificed line is added to supply the required bypass flow, and an orificed and checked line is added to ensure a minimum stem flow regardless of SSCV and SSBV positions. The two-way SSCV's are assumed to have capability in the full-closed position of blocking all flow through the valve. For thrusting operations the SSCV's are operated in standby redundancy. The valves in pulse cooldown system in addition to those in the SSCSS which are utilized remain unchanged except the CSCV's are assigned only a binary function instead of an analog control function.

1.0 INTRODUCTION (Cont'd)

Subsequent sections will deal with the analysis of the "Reference" as opposed to the "Proposed" supply and control coolant networks for the structural-support and pulse-cooling operations. Section 2.0 will describe the engine control concept. Section 3.0 will describe the engine functions and the criticality of these functions for each of the "Reference" and "Proposed" systems. Section 4.0 will discuss the safety evaluation while Section 5.0 will cover the reliability analysis.

2.0 ENGINE CONTROL SYSTEM CONCEPT

The SSCSS can and is planned to have a significant role in reactivity control of the nuclear subsystem. Therefore, to meaningfully evaluate the Reference and Proposed SSCSS's regarding their effects on system safety and reliability, it is necessary to have some definition of the control concept to be utilized for the various engine operational phases.

Discussions with I&C personnel revealed that with the exception of control design objectives, a total control concept at this time has not been established. The design objectives are, in general, to place minimum reliance on control drums and, to the extent practical, maximum reliance on the SSCSS for reactivity and temperature control. Ideally analog control of the drums would be used only to accomplish bootstrap. The control drums then would be moved to the steady state position and held or locked in this position. Temperature control through the startup ramp would be accomplished through the SSCV by controlling the reactivity provided by the SSCSS. Once at the steady-state operation point, control of temperature including compensation for core corrosion losses would be maintained by the SSCV. Chamber pressure during the startup ramp and at the steady state operating point would be maintained by the Bypass Control Valve (BCV). The shutdown ramp, including a dwell time at the throttle point, would utilize the same control loops as for startup and steady state (SSCV position for temperature control and BCV position for pressure control).

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2.0 ENGINE CONTROL SYSTEM CONCEPT (Cont'd)

The above control modes are technically feasible with the currently specified control-drum span worth of about \$4.00 and a SSCSS span worth of about \$2.00 with the exception of at the end-of-reactor life. Assuming a \$1.00 corrosion loss at the end-of-life, the SSCSS lacks sufficient reactivity insertion capability for the throttle condition. The resolution of this system limitation has not been defined at this time. Possible alternatives to eliminate or live with this problem giving consideration to program requirements are listed below in order to safety and reliability preference.

(1) Delete the requirement to throttle at end-of-reactor life and accept the subsequent payload loss.

(2) Redesign the SSCSS to incorporate sufficient reactivity insertion capability to provide the ability to throttle at end-of-life without additional drum reactivity insertion.

(3) Provide the capability during steady state operation to make step change reactivity insertions with the drums to compensate for corrosion losses, but maintain the SSCV as the single temperature control element during the shutdown ramp and throttling. Compensation for corrosion losses by maintaining the drums at other than their orificed position would be at the expense of core life.

(4) Maintain both the SSCV and drums in the control loop for all startups, throttling and shutdowns. Steady state operations control would be accomplished with only the SSCV. With this concept the maximum demand is placed on the SSCV and the drums are moved from their orificed position only as required to meet the temperature demand. This adds additional complexity to the control system and malfunction detection system. Operation with the drums at other than their orificed position would be at the expense of core life.

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2.0 ENGINE CONTROL SYSTEM CONCEPT (Cont'd)

For purposes of this reliability and safety analysis of the Reference and Proposed SSCSS it is assumed that the SSCV is the single element in the control loop to satisfy the temperature demand during startup, steady state, throttling and shutdown. This control mode is consistent with alternatives (1) and (2), and partially applicable to alternative (3). Alternative (4) is not evaluated in this study.

3.0 DISCUSSION OF SSCSS AND PULSE COOLDOWN SYSTEM FUNCTIONS FOR ENGINE OPERATION

3.1 OPERATIONAL SEQUENCE

For the "Reference" SSCSS and pulse cooldown system the following operational sequence is assumed for purposes of this evaluation. Structural coolant supply during thrusting operations is supplied through one SSCV and its two blocking valves (SSBV's). The other SSCV leg is shutdown by maintaining the two blocking valves closed. In the event of a malfunction of the active leg, the two blocking valves in the active leg are closed and SSCSS flow is switched to the standby leg by opening the two block valves in that leg.

At the beginning of pulse cooldown, the bypass flow block valve in the active leg is closed and maintained closed through the entire pulse cooling period. Trickle flow is controlled and maintained to the stems by one of the CSCV valves. When the chamber temperature reaches 1500°R the CSCV is opened full to provide a 4 lb/sec flow rate and the stem block valve in the active leg is opened to allow flow to the nozzle and reflector. At the completion of the cooling pulse (1300°R chamber temperature), the full open CSCV is closed to the trickle flow position and the block valve in the active stem leg is closed. Trickle flow to the stems is then continued as previously described. When no further cooling is required the CSCV is closed.

5.70

3.1 OPERATIONAL SEQUENCE (Cont'd)

For the Proposed SSCSS and pulse cooldown system the following is the operational sequence (refer to Figure 2 for valve identification). For thrusting operations coolant flow to the bypass line is fully supplied by the orificed line off the PDL while stem coolant flow is partially supplied by the orificed and checked stem line. Additional stem coolant flow is supplied by opening $SSBV_1$ and the flow rate is controlled by $SSCV_1$. Block valve $SSBV_3$ is maintained open while $SSBV_2$ and $SSCV_2$ are closed. In the event of a malfunction in the active stem coolant control leg ($SSBV_1$ and $SSCV_1$) the malfunctioned leg is shutdown by closing either or both $SSBV_1$ or $SSCV_1$, closing $SSBV_3$, and opening the standby leg by activating $SSBV_2$ and $SSCV_2$.

For pulse cooling operations one of the CSCV's is opened and maintained open for the entire cooling period. Trickle flow to the stems is supplied through the active leg with flow rate controlled by the SSCV. Without any component malfunctions this would be accomplished with $SSCV_1$ open and controlling the stem flow rate, $SSBV_1$ closed, $SSBV_3$ open, $SSBV_2$ closed and $SSCV_2$ closed. To pulse cool to the nozzle and reflector, $SSBV_1$ would be opened to permit an open flow path to the PDL. In the event of a malfunction, the active leg is closed by shuting either or both $SSBV_1$ and $SSCV_1$, closing $SSBV_3$, and operating $SSBV_2$ and $SSCV_2$ the same as previously described for $SSCV_1$ and $SSBV_1$. When no further cooling is required the full open CSCV is closed.

Utilizing the assumed control concept discussed in Section 2.0, the following are SSCSS and pulse cooling requirements and the criticality of these requirements for each of the engines operational modes.

3.2 CHILLDOWN

There is no known requirement for stem or bypass coolant flow during chilldown although it has been generally considered desirable or at least acceptable to condition these flow paths during this engine 5.71

3.2 CHILLDOWN (Cont'd)

operational phase. In fact, this was the only possible means of operation for the hot bleed engine which contained a single SSCV and no stem or bypass block valves. It is possible, however, that stem flow during childown may be detrimental or even hazardous to system operation. By design, the different stem flow paths within the core offer varying degrees of impedence to coolant flow. The resultant childown of the different flow paths would be non-symmetrical and could produce high LH_2 concentrations in areas of the core possibly causing a nuclear excursion or thermal stress problems. It is recommended that this potential SSCSS problem be investigated by WANL. However, for purposes of this analysis, it is assumed that a maldistributing of stem and bypass flow during chilldown and bootstrap is not detrimental to the engine system.

In the Reference system the block valves could be used to stop coolant flow to the reactor. In the Proposed SSCSS, coolant flow is delivered automatically to the reactor by the orifices in the bypass and stem circuits. No provision is available in the Proposed system to completely block stem and bypass flow.

3.3 BOOTSTRAP

Bootstrap is accomplished with analog drum control to maintain the desired temperature ramp. Bootstrap is assumed to be completed when a 60 psia chamber pressure and 1160°R chamber temperature is reached. The position of the SSCV and thus the quantity of stem and bypass flow is assumed not to be critical during bootstrap providing some coolant is being delivered to the stems.

For the Reference SSCSS, the position of the SSCV is not critical but as a minimum one of the block valves in the stem line must be open to prevent possible system damage. For the Proposed SSCSS, the minimum

5.72

3.3 BOOTSTRAP (Cont'd)

required coolant flow is provided by the orificed stem and bypass lines. As in the case of chilldown for both Reference and Proposed SSCSS's, it is recommended that the active SSCV legs be maintained open as assurance of their operability for later critical operational phases.

3.4 STARTUP

Startup is accomplished by moving the drums to their orificed position and then, with SSCV as the single element in the temperature control loop, ramping through a high I_{sp} path to the steady state operating point. During this startup ramp, maximum demand is placed on the SSCV for reactivity insertion at the throttling point (4250°R and 270 psia).

Maintaining the required levels of stem coolant flow and, to a lesser degree, bypass flow is mandatory during startup to sustain the system and satisfy performance requirements.

3.5 STEADY STATE

Steady state operation is maintained with the SSCV in the temperature control loop and the drums locked or held in their orificed position. All corrosion losses are made up by inserting additional reactivity with the SSCV.

Controlled flow of coolant to both the bypass and stems is critical to prevent system loss and to satisfy performance requirements. Reductions in stem flow could cause retreat from the high I_{sp} operating point while total loss of stem coolant would result in system loss. Increases in stem flow rate would increase core reactivity and total power with subsequent loss of the system unless counteracted. Bypass flow at some minimum rate is required for structural support plate coolant. Bypass flow below this flow rate would result in system damage and possibly failure.

3.6 SHUTDOWN

High I_{sp} shutdown is accomplished the same as startup with the exception

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3.6 SHUTDOWN (Cont'd)

of a dwell time at the throttling point to remove additional decay energy while operating in a high I_{sp} reduced thrust mode. Shutdown is terminated at 2500°R chamber temperature and 150 psia chamber pressure at which time the drums are commanded to their full-in position.

The component functions and their criticality are the same as discussed for startup, Section 3.2.

3.7 TAILOFF

The SSCSS does not have any direct control function during pump tailoff. Flow is controlled through the turbine control circuit until a chamber temperature of 1500°R is reached and a flow of 4 lb/sec is attained. The turbines are then blocked from the system and flow continues by tank pressure until a chamber temperature of 1300°R is reached. Flow is then terminated by closing the propellant shutoff valves.

The position of the SSCV and thus the quantity of stem flow is assumed not to be critical during pump tailoff; however, some stem flow is mandatory to sustain the system. Bypass flow is assumed not to be critical during pump tailoff. That is, it could be high, low, or completely blocked without detrimental consequences on the system.

3.8 COOLDOWN/COAST

During pulse cooldown the valves in the SSCSS supply network must work in conjunction with the valves in the pulse cooling network to provide a direct flow path from the Main Propellant Tank (MPT) to the stems and a direct flow path to the nozzle and reflector. A continuous trickle flow varying from 0.4 to .002 lb/sec is required between pulses for the entire cooling period. The method for obtaining and controlling the desired trickle flow in the Reference and Proposed subsystems is described in Section 3.1. The inability to trickle flow coolant to the stems at the required rate could result in a mission abort due to less efficient use of propellant than planned.

5.74

3.8 COOLDOWN/COAST (Cont'd)

Cooling pulses of 4 lb/sec are obtained by reverse flow through the SSCSS supply network as described in Section 3.1 for the Reference and Proposed subsystems. Failure to provide pulse cooling in the prescribed manner is not considered critical to system survival since the main PFS provides an emergency source for the required coolant. However, utilization of the main PFS would require additional cycling of the PSOV, less efficient use of propellant, and most probably a decision to abort the mission.

4.0 SAFETY EVALUATION

4.1 GENERAL

The safety evaluation of the Reference and Proposed systems was limited to the coolant supply circuit since configuration and material selection for the stems and the structural support plate remain unchanged in the two systems. Each component in the coolant supply circuit was rated in the event of a malfunction for its most severe effect on the system for each of the engine operational phases. The system malfunction effect on engine operation was identified by assigning one of five Hazard Categories.

4.2 HAZARD CATEGORY DEFINITIONS

The five Hazard Categories utilized in this safety evaluation of the SSCSS are defined as follows:

Category 1 - Failures or incipient failures which produce no significant operational degradation or transient condition on the system and require no conscious action by the crew or land control to permit mission completion. Failures of critical safety systems and critical standby-redundant components fall within this category.

Category IIA-Failures, incipient failures or degradations from which the engine can recover and still complete the mission by

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4.2 HAZARD CATEGORY DEFINITIONS (Cont'd)

switching or reverting to a Recovery Mode. Failures in this category produce transient effects which can be tolerated by the system, and which permit time for human judgement to be exercised on the method and desirability of the Recovery Mode. Failures which require the functioning of safety systems or redundant components to preclude Category III conditions fall within this category.

Category IIB-Failures, incipient failures or degradations from which the engine can recover and still complete the mission by <u>immediately</u> switching or reverting to a Recovery Mode. Failures in this category require fast action to remove or lessen the transient condition. Switching to the Recovery Mode is usually accomplished automatically by the malfunction detection system or the engine control system. Failures which require the automatic functioning of safety systems or redundant components to preclude Category IV conditions fall within this category.

Category III-Failures, incipient failures or degradations which require mission abort and switching to an Emergency Mode to effect safe crew return or to prevent danger to the earth's population. Thrust capability of at least F = 30,000 lb and I_{sp} = 500 seconds is required if continued nuclear engine operation is necessary to effect safe crew return or to effect a safe disposal of the nuclear stage.

Category IV- Failures which res   in direct injury to the crew, endanger the earth's population or damage the space craft or other stage modules upon which crew survival depends and for which Emergency Action is required. Failures in this category

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4.2 HAZARD CATEGORY DEFINITIONS (Cont'd)

produce one or more of the following system affects:

(a) Total or partial loss of thrust to $F < 30,000$ lb $I_{sp} < 500$ seconds.

(b) Unsuccessful NE shutdown and/or cooldown which precludes engine restart.

(c) Unsuccessful startup to attain thrust $F \geq 30,000$ lb and $I_{sp} \geq 500$ seconds.

4.3 HAZARD CATEGORY ASSIGNMENTS AND DISCUSSION

The hazard category assignments for each of the components in the SSCSS and pulse cooling supply network for each of the engines operational modes are shown in Figure 3 for the Reference system, in Figure 4 for the Proposed system, and those that are of primary importance regarding system safety are summarized in Figure 5. It can be seen from Figure 5 that better than a 50 percent reduction in component failures having a direct and immediate impact regarding safety is obtained with the Proposed system. No single failure in either the Reference or the Proposed system has been rated Hazard Category IV (direct injury to the crew or danger to the earth's population).

The hazard category assignments used in this safety evaluation and shown in Figures 3, 4 and 5 do not consider as credible: line rupture, valve rupture, orifice failure or multiple component failure. The hazard category assignments were made without consideration for the normal fail position of the valves. For example, for a normally fail closed valve it is considered credible that the valve could fail in a full open position. This was done because a command failure could demand the valve to be in other than the desired position and normal fail positions have not at this time been established for the valves. This policy was applied uniformily to both the Reference and Proposed subsystems and therefore

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4.3 HAZARD CATEGORY ASSIGNMENTS AND DISCUSSION (Cont'd)

is judged to not unfairly bias the safety analysis conclusions. It should be noted, however, that normal fail positions are required for reliability analysis, and the assumed normal fail positions utilized are identified in Section 5.0.

The improved system safety of the Proposed over the Reference system results primarily from the orificed bypass coolant flow in which failure is considered not to be credible and in the protective feature afforded by the orificed stem flow. Failures of the valves controlling stem flow do not normally require immediate response because of the continuous coolant provided by orificed stem line.

The logic for the Hazard Category assignments, particularly those of Category IIB and III, are discussed by engine operational mode in the following subsections.

4.3.1 Childown

Since as stated previously in Section 3.2 there is no known requirement for childown flow in the SSCSS, all Hazard Category assignments for both the Reference and Proposed systems have been made Category I (no significant operational degradation).

4.3.2 Bootstrap

During bootstrap some minimum stem flow is considered to be required for cooling while bypass flow is not considered to be mandatory. In the Reference SSCSS, failure of the block valve (SSBV) to a closed position in the active stem line has been assigned a Category IIB (requires immediate corrective action) while all other components are rated as Category I. In the Proposed SSCSS all component malfunctions are rated as Category I since the orifice in the stem line and the SSCV provide redundant sources of stem coolant.

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4.3.3 Startup

During startup with the drums locked in their orificed position, the SSCSS is used to control reactivity and as such controls the temperature ramp. In the first part of startup in which temperature and pressure are ramped to the throttle point (4250° and 270 psia) maximum demand is placed on the SSCSS. Failure to meet this demand, providing some stem and bypass coolant flow is maintained, would cause operational degradation but not necessarily requiring immediate corrective action for system survival. However, during the pressure ramp to the steady state operational point the SSCV must reduce reactivity in the stems to compensate for the reactivity effects of the steadily increasing total hydrogen inventory in the core. Failure of the SSCV to maintain only the required flow to the stems would result in loss of the system due to excessive chamber temperature unless immediately corrected.

For the Reference SSCSS, the active SSCV and the stem block valve in the standby leg is rated as Category IIB because of the potential malfunction possibility of supplying excessive stem reactivity insertion. The bypass block valve in the active leg is rated as Category IIB because bypass flow is required for structural support plate coolant. The bypass block valve in the standby leg is rated as Category IIB because, if failed open, excessive flow to the bypass line could result in depletion of the stem coolant flow beyond the rate required to maintain the structural integrity of the stems. Though this latter malfunction condition is assigned as Category IIB, a malfunction analysis is required to confirm this hypothesized system response.

For the Proposed SSCSS there are two active sources of stem coolant supply. A single loss of either one of these sources would cause a decrease in reactivity with resultant degradation of engine performance but not loss of the system. Rated performance could be attained by further

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4.3.5 Tailoff (Cont'd)

the stem effluent flow should be sufficient to maintain the structural support plate within its temperature limits during this operating mode.

In the Reference SSCSS only the failure of the stem block valve in the active leg has been assigned a Hazard Category IIB. All other component failures either produce no system degradation or the degradation does not require immediate corrective action.

In the Proposed SSCSS there are two active sources of stem coolant supply and the loss of a single source would not be critical to system operation. Therefore, no hazard category higher than IIA is assigned to any of the components in the SSCSS supply circuit.

4.3.6 Cooldown/Coast

As previously stated, the function of the SSCSS and pulse cooling supply circuit during cooldown and coast is to provide a direct path for trickle flow to the stems and to provide a direct path by means of reverse flow to supply coolant to the nozzle and reflector.

In the Reference system, failure of either stem block valve to an open position would provide a direct flow path to the PDL. This would prevent efficient trickle flow to the stems which would have to be counteracted by more frequent cooling pulses to maintain required temperature limits in the stems. This inefficient use of propellant could necessitate abandoment of original mission objectives and require the performance of contingency actions for safe return of the crew or safe disposal of the nuclear stage. For this reason the two stem block valves have been assigned a Hazard Category III.

The three valves ($CSCV_1$, $CSCV_2$ and CSKV) which permit and control flow from the MPT are all assigned a Hazard Category III. Failure of either of the control valves in a full open position would prevent efficient trickle flow to the stems, possibly requiring a mission abort. Failure of the check valve to open would require the use of the main

5.80

4.3.3 Startup (Cont'd)

opening the active SSCV in the event of check valve failure in the orificed stem line or by blocking the malfunction active SSCV leg and switching to the redundant standby SSCV leg. The above malfunctions have been assigned Hazard Category IIA since they do not require immediate corrective action for system survival. The two SSCV's, however, have the potential malfunction possibility of failing to a full or near full open position and adding excessive reactivity. Immediate closure of the block valve in the leg with the malfunctioned SSCV and the block valve ($SSBV_3$) separating the two legs would be required to sustain the system. Accordingly Hazard Category IIB has been assigned as the worst case malfunction condition to the two SSCV's in the "Proposed" subsystem.

4.3.4 Steady State and Shutdown

During steady state and shutdown the requirements of the SSCSS are the same as they are for startup. These requirements are to provide variable controlled reactivity insertion capability and to provide coolant to the stems and the structural support plate. Therefore, the Hazard Category assignments for the components in the SSCSS supply circuit and the justification are the same as discussed for startup.

4.3.5 Tailoff

Tailoff is performed with the control drums rolled in and propellant is provided by pump pressure to remove decay heat. The purpose of the SSCSS supply circuit during this operational period is to maintain a sufficient quantity of coolant to sustain the structural integrity of the stems and the structural support plate. Continued stem cooling during tailoff is mandatory but the rate of the stem coolant flow within the limits of the 3-way SSCV is not considered critical. Bypass coolant flow is also not considered critical during tailoff since

5.81

4.3.6 Cooldown/Coast (Cont'd)

PFS for emergency coolant supply, possibly again requiring a mission abort.

In the Proposed subsystem there are four component failures which could require a mission abort and accordingly have been assigned as Hazard Category III. Three of the four would prevent efficient trickle flow to the stems. These three are: the check valve in the stem orifice line by failing to close, thus allowing back flow to the PDL; block valve $SSBV_2$ by failing open; and $SSCV_2$ by failing open to some position greater than that required for controlled trickle flow to the stems. The fourth Hazard Category III assignment is for the CSKV which if failed closed would require the less efficient use of the main PFS for pulse coolant supply to the reactor.

5.82

RELIABILITY ANALYSIS

The full flow reference design has several undesirable reliability features in the method of providing flow to the support structure. The reference design CSCV's have a complex functional requirement. They must control feed pressure during coast and thrusting, control relatively low stem flow rates and provide reflector pulsed flow during cooldown. A fail in position or fail full open of the CSCV's cannot be tolerated because the failure cannot be isolated. The SSCV's have a double function of proportioning full thrust flow and are flowed in reverse for pulse flow. Since they are each proportioning the entire support structure flow they cannot be actively redundant. The reference design requires one of the SSBV's to be cycled for every pulse along with the CSCV cycling from low stem flow to full open for pulse flow.

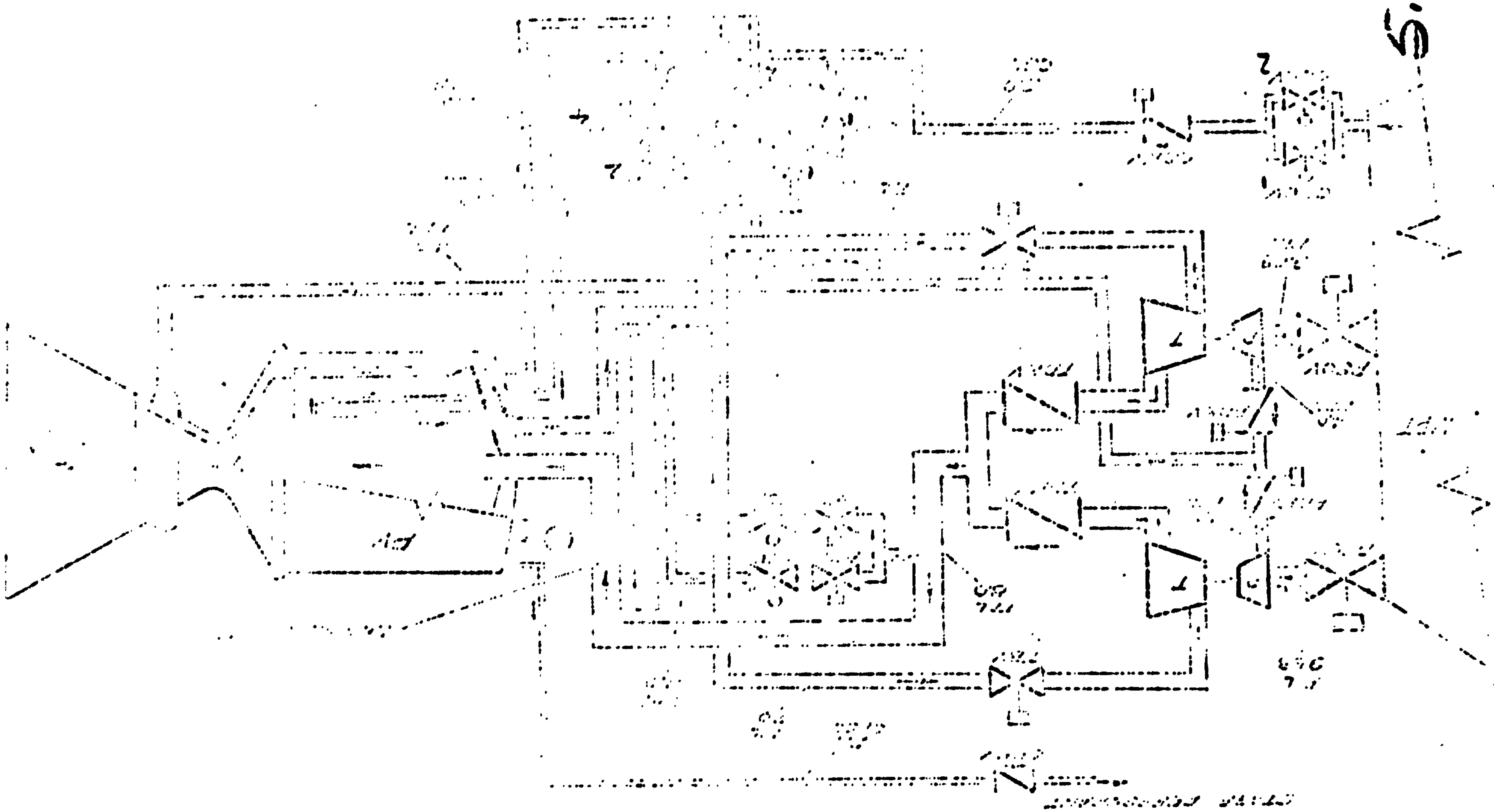
The proposed redesign represents an approach to simplify the functions of some of the valves and to require fewer valves to be functional during pulse cooling. The introduction of orificed flow to provide constant minimum required stem and bypass flow reduces the total control span on the SSCV's. The use of two-way SSCV's simplifies their design and also permits active redundancy if reaction to failure is time sensitive. (However standby operation offers higher system reliability and location of the third blocking valve ($SSBV_3$) is predicted upon stand-by redundancy).

Reversing the order of the SSCV's and their blocking valves (SSBV's) permits the introduction of cooldown flow between these valves. Cycling one of the SSBV's is all that is required for pulse flow control. This reduces the CSCV from a complex shut-off and control valve to a simpler normally closed two-way shut-off valve which is opened and remains open through each entire cooldown period.

A detailed description of the assumed functional requirements and the mathematical models representing the functions of the two systems

5.0 RELIABILITY ANALYSIS (Cont'd)

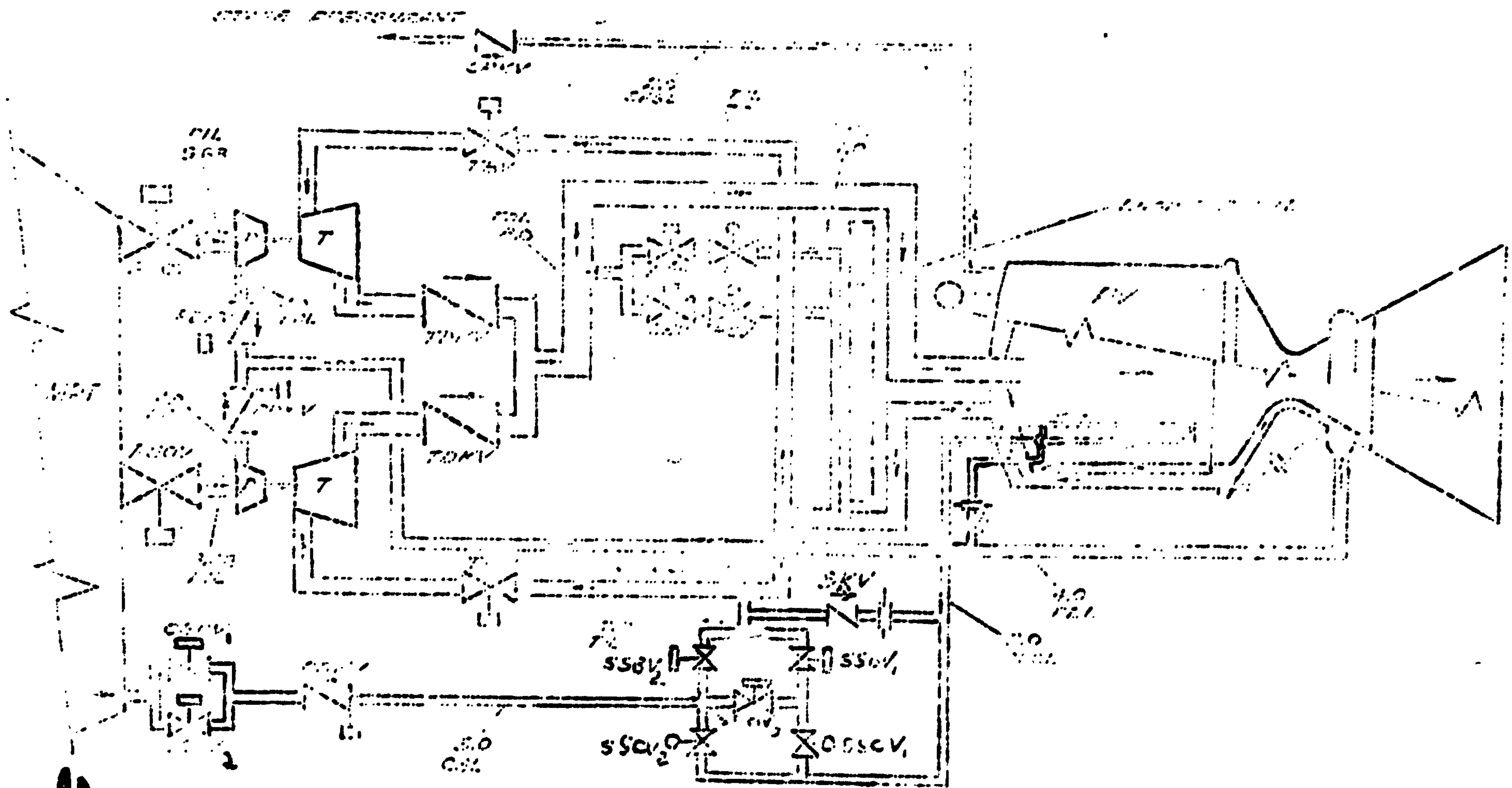
are presented in Appendix A. Component failure rates derived from previous test experience were applied to models for a single thrusting cycle and an 83-pulse cooldown cycle. The probability of successfully completing one thrusting cycle including cooldown is estimated to be 0.975 for the Reference SSCSS and cooldown system versus the Proposed system probability of 0.989. This constitutes a 50% reduction in failure rate (from 0.025 to 0.011) for a single thrusting cycle. The significance of these numbers is more apparent when extrapolated to a 10 cycle mission. The Reference design exhibits a reliability of 0.776 while the Proposed system reliability is 0.895.



5.85

FIGURE 7.

FULL FLOW ENGINE - PROPOSED COOLANT/SSCSS SYSTEM



5.86

COOLDOWN AND SSCSS SAFETY EVALUATION

FULL FLOW REFERENCE ENGINE

SUBSYSTEM & COMPONENTS	HAZARD CATEGORY ASSIGNMENTS DURING						
	CHILLDOWN	BOOTSTRAP	STARTUP	STEADY STATE	SHUTDOWN	TAILOFF	COOLDOWN
ACTIVE SSCSS LEG							
$SSCV_1$	I	I	IIB	IIB	IIB	IIA	I
$SSBV_1$ (STEM)	I	IIB	IIB	IIB	IIB	IIB	III
$SSBV_2$ (BYPASS)	I	I	IIB	IIB	IIB	I	I
STANDBY LEG							
$SSCV_2$	I	I	I	I	I	I	I
$SSBV_3$ (STEM)	I	I	IIB	IIB	IIB	IIA	III
$SSBV_4$ (BYPASS)	I	I	IIB	IIB	IIB	IIA	I
PULSE COOL LEG							
$CSCV_1$	I	I	I	I	I	I	III
$CSCV_2$	I	I	I	I	I	I	III
CSKV	I	I	I	I	I	I	III

COOLDOWN & SSCSS SAFETY EVALUATION

FULL FLOW ENGINE - PROPOSED COOLDOWN/SSCSS SYSTEMS

SUBSYSTEM & COMPONENT	HAZARD CATEGORY ASSIGNMENTS DURING						
	CHILLDOWN	BOOTSTRAP	STARTUP	STEADY STATE	SHUTDOWN	TAILOFF	COOLDOWN
BYPASS ORIFICE LINE	FAILURE NOT CREDIBLE						
STEM ORIFICE LINE							
ORIFICE	FAILURE NOT CREDIBLE						
CHECK VALVE	I	I	IIA	IIA	IIA	IIA	III
ACTIVE SSCSS LEG							
$SSCV_1$	I	I	IIB	IIB	IIB	IIA	IIA
$SSBV_2$	I	I	IIA	IIA	IIA	IIA	IIA
STANDBY SSCSS LEG							
$SSCV_2$	I	I	IIB	IIB	IIB	IIA	III
$SSBV_2$	I	I	I	I	I	I	III
PULSE COOL LEG							
$CSCV_1$	I	I	I	I	I	I	IIA
$CSCV_2$	I	I	I	I	I	I	IIA
CSXV	I	I	I	I	I	I	III
$SSBV_3$	I	I	I	I	I	I	IIA

S-55

FIGURE 5.

SAFETY SUMMARY OF REFERENCE AND PROPOSED COOLDOWN/SSCSS SYSTEMS

CONFIGURATION	NUMBER OF FAILURE MODES RESULTING IN		
	MISSION RECOVERY WITH IMMEDIATE CORRECTIVE ACTION (HAZARD CATEGORY IIB)	MISSION ABORT BUT WITH EMERGENCY MISSION CAPABILITY (HAZARD CATEGORY III)	SYSTEM LOSS REQUIRING EMERGENCY ACTION TO PREVENT PERSONNEL INJURY (HAZARD CATEGORY IV)
FULL FLOW REFERENCE ENGINE COOLDOWN/SSCSS SYSTEM	17	5	NONE
FULL FLOW ENGINE-PROPOSED COOLDOWN/SSCSS SYSTEM	5	4	NONE

5.87

APPENDIX A

RELIABILITY MATHEMATICAL MODELS OF REFERENCE FFE AND PROPOSED REDESIGN OF SUPPORT STRUCTURE COOLANT SUBSYSTEM COOLDOWN CONTROL AND SUPPLY NETWORKS

A. REFERENCE DESIGN

I. ASSUME

$SSBV_1$ and $SSBV_2$ are N.O., $SSBV_3$ and $SSBV_4$ are N.C.

SSCV's fail in place but do not prevent reverse pulse flow.

II. SEQUENCE OF OPERATION

THRUSTING SEQUENCE

A. NORMAL

$SSCV_1$ controls and CSKV prevents reverse flow.

B. FAILURE

$SSCV_1$ fails in place then $SSBV_1$ and $SSBV_2$ close, $SSBV_3$ and $SSBV_4$ open and $SSCV_2$ controls and CSKV continues to prevent reverse flow.

COOLING SEQUENCE

A. NORMAL STEM FLOW

$SSBV_1$ and $SSBV_2$ close while $CSCV_1$ opens partially for stem flow.

B. PULSING

$SSBV_3$ opens and closes for each pulse while $CSCV_1$ opens wider and closes to stem flow position for each pulse. $SSBV_1$ remains closed. Pulsing through $SSBV_3$ is preferred because it is more probable to fail closed while $SSBV_1$ will more probably fail open preventing further pulse cooling.

C. FAILURE MODE

1. Stem flow and pulse flow

If $CSCV_1$ fails to control, CSCV must close and $CSCV_2$ controls.

2. Pulse flow.

If $SSBV_3$ fails to open then pulse flow thru $SSBV_1$.

5.90

III. MATH MODEL

CS = SSCV = Support Structure Coolant Valve

SC = CSCV = Coolant Supply Control Valve

BV = SSBV = Support Structure Block Valve

R_{STEM} = Prob. of Stem Coolant Flow Control

R_{PULSE} = Prob. of Pulse Coolant Flow Control

R network = $R_1 \times R_2 \times R_3$

R_1 = Probability of thrusting with no component failures or successful thrusting with isolateable component failures

R_2 = Coolant Supply Network -- probability of cooldown with no component failures or successful cooldown with isolateable component failures.

R_3 = Pulse cooling - probability of no blocking valve failures or probability of successful pulse cooling with isolateable block valve failure.

R_1 = Rcont-cv1 + (1-Rcont-cv1) Rc-bv1 Rcbv2 Robv3 Rcbv4 Rcont-cv2 Rrev-1k · CSKV

R_2 = Rstem-sv1 Rpulse-sv1^m+ (1-Rstem-slv Rpulse-sv1) Rc-sv1 Rstem-sv2 Rpulse-sv2^m

R_3 = Ro-bv3^m Rc-bv1 + (1-Ro-bv3) Rc-bv1^m

where m = number of pulse cooldown cycles

B. PROPOSED DESIGN

I. ASSUME

$SSBV_2$ is N.C., $SSBV_1$ and $SSBV_3$ are N.O.

SSCVs fail in place and, if failed, prevent reverse pulse flow in their leg, CSCVs are N.C. two-way valves.

5.41

II. SEQUENCE OF OPERATION

THRUSTING SEQUENCE

NORMAL

$SSBV_1$ remains open, $SSCV_1$ controls, $SSBV_2$ and $SSCV_2$ remain closed, $SSBV_3$ remains open. BKV opens, CSKV prevents reverse leakage.

FAILURE

$SSCV_1$ fails to control then $SSBV_1$, and $SSBV_3$ close, $SSBV_2$ opens and $SSCV_2$ controls. BKV remains open.

COOLING SEQUENCE

NORMAL

$SSCV_1$ controls stem flow, $SSBV_1$ pulses, $SSBV_3$ remains open.

FAILURE

If $SSBV_1$ fails to close then $SSCV_1$ is closed, $SSBV_3$ is closed and $SSBV_2$ pulses and $SSCV_2$ controls. If SSCV fails to control then $SSBV_3$ and $SSBV_1$ close, $SSBV_2$ pulses and $SSCV_2$ controls stem flow.

III. MATH MODEL

Ro = RoRro = Probability valve opens and remains open

Rc = RcRrc = Probability valve closes and remains closed

Rcont = Probability valve controls flow at desired rate

cv = SSCV = Support Structure Coolant Valve

bv = SSBV = Support Structure Block Valve

ckv = Check Valve

R network = $R_1 + R_2$

R_1 = Probability of no component failures during thrusting and no component failures during cooldown or successful cooldown with isolatable component failures

R_2 = Probability of successful thrusting with isolatable component failures and subsequent successful cooldown with isolatable thrusting component failures.

5.92

R_1 = Rcont-cv1 Rrev.lk-ckv Rc-bv1 Rcont-cv1 + (1-(Rc-bv1))

Rc-cv1 Rc-bv3 Ro-bv2^m Rcont-cv2

R_2 = (1-(Rcont-cv1))Rc-bv1 Ro-bv2 Rc-bv3 Rcont-cv2 Ro-bv2^m

Rcont-cv2 Rrev.lk:bkv

where m = number of pulse cooldown cycles

SINGLE CYCLE FAILURE RATES APPLIED TO MATH MODELS

Definitions: R = Probability of successfully:

Ro = opening

Rro = remaining open

Rc = closing

Rrc = remaining closed

Rcont = controlling

N.O. = normally open, N.C. = normally closed

	Type	Ro	Rro	Rc	Rrc	Rcont	Rrev.leak (Li)
CSCV	Shutoff and control valve	$.9_4 25$	$.9_4 40$	$.9_4 8$	1.0	$.9_3 83$	-
CSOV	Two-way valve	$.9_4 25$	$.9_4 40$	$.9_4 8$	1.0	-	-
CSKV	Actuated Closed check valve	1.0	1.0	1.0	1.0	-	$.9_4 6$
SSCV	Three-way control	-	-	-	-	$.9_3 66$	-
SSCV	Two-way control	-	-	-	-	$.9_3 83$	-
SSBV & CBV	Two-way block N.O.	1.0	1.0	$.9_4 25$	$.9_4 4$	-	-
	Two-way block N.C.^{2}	$.9_4 25$	$.9_4 4$	1.0	1.0	-	-
BKV	Check valve	1.0	1.0	1.0	1.0	-	$.9_4 6$

5.93

MEMORANDUM

TO: P. P. Ventura

DATE: 24 November 1969
7850:M0343

FROM: J. H. Ramsthaler

SUBJECT: Reliability and Safety Review of "Engine System Evaluation for Alternate Sources for Turbine Drive Gas, Hot Bleed Engine, S-054-015"

COPIES TO: J. J. Beereboom, W. M. Bryan, D. Buden, D. S. Duncan, R. V. Evleth, R. B. Glasscock, J. M. Klacking, C. F. Leyse, B. Mandell, I. L. Odgers, D. E. Price, E. A. Sheridan, L. A. Shurley, S. A. Varga, E. J. West, W. O. Wetmore, A. S. Woodham, R. B. Wright
NTO: W. H. Bushnell

REFERENCES:

(a) Memo 7850:M0318, dtd 30 Oct. 69, W. M. Bryan to P. P. Ventura, Subject: Reliability Review of Hot Bleed Engine Trade Studies

(b) Memo 7850:M0239, dtd 6 Aug. 69, E. B. Cleveland to R. B. Wright, Subject: Reliability Evaluation of Diluent and Bolt Coolant Concepts - Trade Study 006

(c) Memo 7850:M0192, dtd 19 Aug. 69, E. B. Cleveland to J. L. Watkins, Subject: Reliability Comparison of Three Turbine Drive Gas Systems

The subject report has been reviewed, as requested by Reference (a), and is satisfactory for submittal as a nonmanagement approved study. This restriction is considered necessary because a safety analysis was not performed in support of this study. It does not appear worthwhile to do a safety analysis at this time since the hot bleed design is no longer being considered, however, the study is incomplete without this evaluation.

The study was reviewed for Reliability considerations and is in general agreement with the reliability analyses of References (b) and (c).

J. H. Ramsthaler, Manager
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
11/24/69
CLASSIFYING OFFICER DATE

5.94

MEMORANDUM

TO: S. A. Varga

DATE: 25 November 1969
7850:M0346

FROM: E. J. West

SUBJECT: Reliability Apportionment of Current Reference Engine Concept

COPIES TO: J. J. Beereboom, D. Buden, W. E. Campbell, A. D. Cornell, R. W. Froelich, R. B. Glasscock, J. M. Klacking, L. E. Little, B. Mandell, J. H. Ramsthaler, E. A. Sheridan, L. A. Shurley, J. J. Stewart, T. R. Thompson, 7850 Personnel
NTO: W. H. Bushnell

ENCLOSURE: (1) NERVA Engine System Reliability Apportionment

A preliminary reliability apportionment has been made for the current NERVA Reference Engine Full Flow Concept as defined by Drawing Numbers 1136390 and 1136391. The engine system was divided into subsystem and component groups as specified by the NERVA ENGINE SPECIFICATION TREE (Dwg. 1137101).

Apportioned reliability numbers are included for components for which WANL has responsibility. These values are based on a hot bleed analysis received from WANL with the fuel element prediction lowered from approximately .99 to .90 to account for the full flow design and its longer life requirements.

The apportioned reliability values are presented in Enclosure (1). In addition, Enclosure (1) includes the predicted reliability values for each of the subsystems and components that were used as the basis of the apportionment. In deriving the apportionment, a mission of ten cycles was assumed to facilitate calculations. A 60-cycle calculation has a significant effect on the predicted reliability but little effect on the apportionment. (The 60-cycle predicted engine reliability is .33)

For expediency, this memo is presented without substantiation of the prediction. That analysis will be documented in a subsequent memo.

E. J. West
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

Enclosure (1)
7850:M0346

NERVA ENGINE
SYSTEM RELIABILITY APPORTIONMENT
(10-CYCLE MISSION)

	RELIABILITY*	
	Predicted	Apportioned
NERVA ENGINE	.832694	.995
NUCLEAR SUBSYSTEM	.888498	$.9_{2}6823$
FUEL ELEMENTS	.900000	$.9_{2}7184$
CLUSTER HARDWARE	$.9_{2}7623$	$.9_{4}329$
CONE PERIPHERY	$.9_{2}6585$	$.9_{4}037$
SUPPORT PLATE & PLENA	$.9_{3}360$	$.9_{4}8195$
INTERNAL SHIELD	$.9_{4}50$	$.9_{5}859$
REFLECTOR ASSEMBLY	$.9_{2}7194$	$.9_{4}2088$
CONTROL DRUM DRIVE ASSEMBLY	$.9_{2}6446$	$.9_{3}8998$
SUPPORT STRUCTURE COOLING CONTROL SYSTEM	.988672	$.9_{3}677$
SSCV & ACTUATORS (2 ea)	$.9_{2}8251$	$.9_{3}741$
SSBV (4 ea)	$.9_{2}8152$	$.9_{3}760$
CSKV	$.9_{3}300$	$.9_{4}80$
CSCV	$.9_{2}6167$	$.9_{3}891$
LINES	$.9_{3}460$	$.9_{4}85$
CSL (3.0)		
SCBL (3.0)		
SSCL (3.0)		
SSCL (3.0)		

* Subscript denotes number of 9s, i.e. $.9_{2}6823 = .996823$

5.96

	RELIABILITY Predicted	RELIABILITY Apportioned
NERVA ENGINE (cont.)		
PROPELLANT FEED SYSTEM	$.9_{2}1809$	$.9_{3}766$
PSOV	$.9_{2}7862$	$.9_{3}710$
PDKV	$.9_{3}300$	$.9_{4}80$
TBV	$.9_{2}7463$	$.9_{3}644$
TDKV	$.9_{2}8701$	$.9_{3}480$
BCV (2 ea)	$.9_{2}8002$	$.9_{3}732$
BBV (2 ea)	$.9_{2}7463$	$.9_{3}642$
TPA	$.9_{2}8771$	$.9_{3}831$
PIL	$.9_{4}80$	$.9_{5}67$
PPL	$.9_{3}780$	$.9_{4}78$
TIL	$.9_{3}740$	$.9_{4}77$
TEL	$.9_{3}740$	$.9_{4}77$
TBL	$.9_{3}740$	$.9_{5}260$
ENGINE PURGE UNIT	$.9_{2}8988$	$.9_{3}5$
PNEUMATIC STAGE TANK PRES.	$.9_{3}280$	$.9_{4}794$
SPKV	$.9_{3}300$	$.9_{4}80$
SPSL	$.9_{4}80$	$.9_{6}40$
DESTRUCT SUBSYSTEM	$.9_{4}20$	$.9_{5}77$
NOZZLE ASSEMBLY SUBSYSTEM	$.9_{2}1114$	$.9_{3}746$
NOZZLE & BOLT COOLANT LINE & ORIFICE	$.9_{2}619$	$.9_{3}891$
NOZZLE SKIRT	$.9_{2}660$	$.9_{4}03$
NOZZLE SKIRT EXTENSION	$.9_{2}830$	$.9_{4}515$

5.97

	RELIABILITY	
	Predicted	**Apportioned**
NERVA ENGINE (cont.)		
INSTRUMENTATION & CONTROL SUBSYSTEM	.965438	$.9_{3}014$
EPIC	.971256	$.9_{3}1842$
WIRING HARNESS	$.9_{3}854$	$.9_{5}585$
NONNUCLEAR INSTRUMENTATION	$.9_{2}7088$	$.9_{4}173$
NUCLEAR INSTRUMENTATION	$.9_{2}7088$	$.9_{4}173$
POWER SUPPLY	$.9_{4}710$	$.9_{6}177$
THRUST STRUCTURE SUBSYSTEM	$.9_{3}640$	$.9_{5}0$
UPPER	$.9_{3}888$	$.9_{5}689$
MIDDLE	$.9_{3}835$	$.9_{5}542$
LOWER	$.9_{4}210$	$.9_{5}781$
SHIELD SPACER	$.9_{5}60$	$.9_{6}889$
EXTERNAL SHIELD SUBSYSTEM	$.9_{4}65$	$.9_{6}0$
GIMBAL ASSEMBLY SUBSYSTEM	$.9_{3}425$	$.9_{4}84$
GIMBAL ACTUATORS & SUPPORT RODS	$.9_{3}550$	$.9_{4}875$
GIMBAL BLOCK	$.9_{3}875$	$.9_{5}652$
PRESSURE VESSEL & CLOSURE SUBSYSTEM	$.9_{4}$	$.9_{5}7$

M E M O R A N D U M

TO: C. W. Funk

DATE: 10 December 1969
7850:M0361:EJW:jak

FROM: J. H. Ramsthaler

SUBJECT: Materials Test Plan Review

COPIES TO: D. Buden, A. D. Cornell, W. E. Campbell, W. E. Durkee, C. E. Dixon, J. W. Conant, C. W. Funk, L. D. Johnson, V. Kahle, C. K. Leeper, D. Lamvermeyer, B. Mandell, I. L. Odgers, W. E. Stephens, L. Shurley, H. L. Springer, M. Lev, W. O. Wetmore, Section 7850 Personnel

ENCLOSURE: (1) Reliability Audit of Materials Test Plan 12-5-69

A reliability review has been made of the current materials test planning. Detailed comments are provided in Enclosure (1).

The materials test plan is generally adequate for engine PDR. However, the documents should not be released until the many inconsistencies noted in Enclosure (1) are corrected.

From a Reliability viewpoint the data maturity and the schedule of data maturity are generally inadequate for component design PDR. It is felt that at least "A" type maturity of data is required before component PDR for all critical design problem areas affected by material properties. These critical problems related to material properties should be distinctly identified in the plan so they are distinguishable from the material properties for which design allowables are required which will also require A or B class data.

It is anticipated that some of these critical problems and some of the material design allowables will require complete statistical definition of the radiation effects. The irradiated sample sizes presented in the plan are inadequate to perform any significant statistic evaluation.

The radiation effects testing is apparently based on the judgement that the selected materials will be acceptable. The limited sample sizes to be irradiated will not statistically refute or prove this judgement. If an insignificant shift in mean values is experienced, the unirradiated mean and variance will be used. This assumes that irradiation does not effect the data spread. This hypothesis will not be adequately tested. If an apparently significant shift is detected then the material may be rejected. With small sample sizes the risk is high of rejecting acceptable material. If a significant shift is detected then additional irradiated samples may be desirable before continuing with unirradiated testing. The results of initial testing should effect the sequence of tests and the numbers of tests to follow. This kind of logic is not apparent in the current plan.

The materials testing is an important part of the design for reliability methodology. The reliability program plan (R-101) requires that all testing evolve from a systematic study of failure modes. Therefore, the materials test plan should reflect this and present an integrated effort by all of the technical disciplines concerned with materials properties. Furthermore, NRO should not submit a Materials Test Plan which does not include WANL requirements and desired testing.

All materials testing on the NERVA program should be designed with a common philosophy as a basis for both test planning and statistical analysis of the results. This will avoid duplication of testing and the compatibility of the final results will in some instances provide definition of material properties over a broader range of environments.

for C J West
J. W. Ramsthaler, Manager
Reliability & Safety Analysis Section
Nuclear Rocket Operations

APPROVED:

B. Mandell
B. Mandell, Manager
Engine System Department
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
[illegible]
CLASSIFYING OFFICER DATE

ENCLOSURE (1)

RELIABILITY REVIEW OF MATERIALS TEST PLANS

CONDUCTED BY

COMPONENT ANALYSIS GROUP

RELIABILITY AND SAFETY ANALYSIS SECTION

DECEMBER 1969

CONTENTS

5.1.1

REVIEW OF MATERIALS TEST PROGRAM

I. SUMMARY AND CONCLUSIONS

Two basic forms were presented as the test plan to be released. These were: the Identification of Materials Problems and Summary of Materials Data Priority and Maturity.

The problem sheet was assessed for: completeness of components covered; adequacy of predicted environmental range; completeness of materials, including form (i.e., forging, sheet, etc.); and identification of all material problem areas. In order to assure that identified problems would be properly investigated, it was necessary to review the individual material test plans, even though the plans were not updated to conform with recent changes in the overall test program.

The Data Priority and Maturity Summary was compared for: completeness of materials listing, including material form; completeness of material properties; compatibility of test environmental levels with predicted environment; and adequacy of maturity of data and scheduling with respect to program milestones.

The Radiation Effects Group has prepared a comprehensive test matrix, which was compared with the Materials radiation test plans.

In the course of the review, discussions were held with Materials, Structures, Thermal, Radiation Effects, and the various Design Projects.

It was concluded that the Materials Test Plan is generally adequate for Engine PDR requirements. However, the documents should not be released until the many inconsistencies between scheduling documents and specific test plans are corrected. In addition, many of the irradiated sample sizes appear to be inadequate to perform significant statistical evaluation.

From a Reliability viewpoint the Plan appears adequate for Engine PDR, but the data maturity and the schedule of data maturity are inadequate for component design milestones. It is felt that at least A type maturity of data is required before component PDR for all critical design problem areas affected by material properties. These critical problems to material properties are not well defined in the plan.

NRO should not submit a Materials Test Plan which does not include WANL requirements and planned testing. Issuance of an integrated plan will assure a common philosophy of test planning, will avoid duplication of testing, and will assure that analysis of data and final results will be compatible.

Specific problems which resulted in these general conclusions are presented in the following sections. It should be noted that many of the discrepancies are due to the lack of test plan updating to reflect recent changes in the program.

II. GENERAL COMMENTS

A Materials Program Plan should be presented with the forms explaining the overall intent of the materials test plan and what each of the documents contain and are intended to convey. The technique of providing for contingencies should be explained. The plan should be presented as a sequential series of testing where the initial results are allowed to modify subsequent tests within certain restraints.

A. IDENTIFICATION OF MATERIAL PROBLEM FORM

1. The problems for the prime material should be listed separately from the problems for the backup material since, in some cases, they differ.

2. The specific Mechanical and Physical Properties that are problems should be listed.

3. The priority of each problem should be listed.

4. The maturity of data required for each problem should be defined.

5. All temperatures should be expressed in degrees Rankine to be compatible with other program documents.

B. PRIORITY AND MATURITY SUMMARY

1. The material and test plan should be part of the major title on each page rather than repeated on each line in a column.

B. PRIORITY AND MATURITY SUMMARY (Cont'd)

2. The temperature under test requirements for irradiation and property testing is not clear - separate columns should be provided for the Radiation Exposure Temperature and the Material Property Test Environment. This is also true for the radiation atmosphere and the test atmosphere. There is no explanation to cover the temperature cycling during radiation exposure.

C. SPECIFIC MATERIALS TEST PLANS (M SERIES DOCUMENTS)

1. For each property to be tested, comments should be added presenting methods of arriving at sample sizes and numbers of heats, and specimens within heat including data sources, if any.

2. It is not clear how the decisions were made that certain properties are "critical to design". The basis for these decisions should be presented.

3. For the unirradiated testing, the guiding document used for establishing the numbers of tests to be conducted was T.D. 28, which specifies that 15 degrees of freedom are required to estimate the variation of a particular material property. This directive was assumed to apply to all mechanical properties for which estimates are required for design purposes. In order to determine whether planned tests will satisfy this requirement, estimates of within heat and among heat variations are required. Given these estimated variations, the number of heats and specimens within heats which must be tested to satisfy T.D. 28 can be determined.

This procedure was utilized to establish the material test requirements for the critical material properties. As a result, the number of specimens scheduled for testing are, in general, highly acceptable.

4. A similar type procedure for determining test sample sizes should be utilized by WANL.

5. In some cases, however, it is recommended that the number of tests should be increased, since prior data, in these cases, indicates high within heat variations. These are presented in the following table:

5.104

MATERIAL	TEST TYPE	CURRENTLY PROPOSED SPECIMENS/HEAT	RECOMMENDED SPECIMENS/HEAT
718 Alloy (Forging, Sheet, Bar)	Tensile, Facture Toughness	5	8
Ti-6Al-4V Alloy Sheet	Tensile	5	8
UDIMET 630	Tensile, Fracture Toughness	5	8

6. The design changes recently implemented for the Skirt Extension have made obsolete the material test program presented for Graphite Composite. No revised test plan is available for review.

7. The corrosion and contamination tests plans were also not available for review.

8. Bearing and Lubricant Test Matrix M-11

a. Initial material screening of various candidates - The durations of these tests are not presented. Discussion with materials personnel revealed that these are intended, in general, to be tested to failure. This is not indicated in the plan.

b. Bench tests to evaluate prime candidates - It is indicated that all tests will be continued for 10 hours and 60 stop-start cycles. From a Reliability standpoint, this is unacceptable since only the initial and final hardware conditions at the required engine life can be measured. It is suggested that groups of units be tested to specified durations exceeding the required life in order to permit estimation of trends in degradation if they exist.

D. TEST SCOPE DOCUMENTS

In general, the test scope documents are acceptable, since they provide complete and comprehensive discussions of the types of information required from the testing. However, there appear to be severe discrepancies between the test scopes and the actual test plans resulting from the test scope documents. For example, the test scope for 18 Ni Maraging Steel requires eight mechanical and physical properties, while the test plan presented for this material presents tests for determining only 3 of these properties.

III. RADIATION EFFECTS TESTING

An overall plan should be coordinated and agreed upon jointly by Rad. Effects and Materials. The plan developed by Rad. Effects should be modified to consider the test facility capabilities, a current complete materials list including the material forms, and the environmental levels. After approval, this plan should be rigidly adhered to.

The current plan does not provide for the determination of threshold values. The audit did not determine the impact of not defining threshold levels. If this is important, then the plan should consider it.

The designers are considering additional materials not currently included in the plan. This may be due to recent developments since the plan was defined.

There is some question concerning the forms of materials and the need for irradiating some materials. For instance, the following materials are listed as having radiation effects as a problem, but are not included in the radiation plan.

Ti - 6Al-4V (Sheet)

Ti - 5Al-2.5 S_n ELI (Sheet)

7039-T63 Sheet

Al 2024 Forging

Waspalloy Bar

UDIMET 630

A286 Bar and Forging

301 SS Sheet

In general, the sample sizes are considered minimal. Any statistical inferences will have low confidence. The AG Carb plan contains only two tests at each condition. This is unacceptable, since it will not permit any estimation of variation and very poor estimates of means.

An attempt was made to superimpose the Materials Plan on the Radiation Effects proposed matrix. This was difficult to do since some conditions do not fall within the matrix. Any testing planned by WANL on these materials should

S.1C6

III. RADIATION EFFECTS TESTING (Cont'd)

also be included before any conclusion can be made about the overall conformance to the proposed matrix.

IV. COMPONENT PROBLEM AREAS

During the review of the impact on design of changing to the Full Flow Engine concept from the Hot Bleed Engine, critical materials problems were identified for the major components. The Materials Test Plan was reviewed to verify that tests were planned for all of these anticipated problems. The results are summarized in Table I and show four items that apparently are not covered:

1. No rad. effects tests are scheduled for A286 material. The reference memo on Table I indicate that this material may replace Titanium and Inconel for the Turbine Rotating parts.

2. There are low cycle fatigue tests planned for prime Pressure Vessel cylinder and closure 7039-T63 aluminum but none are scheduled for the backup material 6061-T6.

3. Compressive strength data is required for the Thrust Structure materials, however, no compressive tests are listed for Ti-6Al-4V and no tests of any kind for the sheet form of 2024-T62 aluminum. Annealed sheet is noted as being the material form to be used for the Upper, Middle and Lower Thrust Structure. Sheet 6061-T6 and 7039-T63 aluminum are also listed as being considered for these components. No compressive tests are scheduled for either of these materials, and no tests of any kind for the sheet form of 7039-T63.

4. The effects of Pressure Vessel seal wear with pressure cycling were posed as a possible problem by the reference memo on Table I, but no PV seal tests are listed. Tests are planned for 301SS seals and MoS_2 lubricant and this may be acceptable to the PV problem.

It is possible that data is available for the questionable areas noted above, but this is not evident from the test plan.

The following sections discuss specific problems related to the major engine components.

5.107

A. TURBOPUMP ASSEMBLY

1. Aluminum 6061 and 7075 are being considered for the hydraulic inducer turbine rotor, however, no damping tests are planned for forgings of this material. The damping data will be required to predict the blade strength. In addition, the tensile tests for "B" type data are not scheduled until September CY'71 and this data will be required by component PDR for an intermediate stress analysis of the primary stresses in the TPA.

2. The turbine/pump housing is noted as sheet and forging material, however, the present design uses welded 347 castings. Tests of this form should be included in the test matrix.

3. The inducer shaft of Inconel 718 should be added to the TPA Identification of Materials Problems sheet. The turbine shaft should be evaluated as a final machined part because its fabrication results in extensive residual and re-entrant stresses.

4. There is no test planned for thermal expansion of 347 sheet or tube. Has it been determined that the data from forging tests will be applicable for sheet and tubing?

5. The maturity of data for the critical TPA failure mode was reviewed and is summarized in Table II. The properties required for both the prime and backup materials for rotor rupture and blade fatigue are listed and the schedule of data maturity shown. Questions are noted in the Remarks column. It is not apparent from the tabulation why a higher maturity of data is scheduled earlier for the backup material tensile properties than for the prime material.

B. NOZZLE

1. Complex composite structures, such as U tubes require precise evaluation of axial bend stress due to cyclic axial thermal loading. This requires a panel section to be tested rather than a simple material specimen to account for shape stiffness.

C. NOZZLE SKIRT [illegible]NSION

1. The skirt [illegible]ll be subjected to dynamic transverse bending stresses

5.11

C. NOZZLE SKIRT EXTENSION (Cont'd)

and requires the evaluation of the bending modulus of rupture. This also requires a typical panel section as a specimen to account for composite part stiffness.

2. 347 is used extensively in the nozzle assembly in the TPA. Hydrogen embrittlement is listed as a problem, no hydrogen embrittlement tests are scheduled.

3. The AG Carb skirt extension is the prime candidate by TD from NASA. The backup design is a film cooled 347 sheet concept, but is not listed on the plan.

4. The materials test plan does not reflect all the actual physical and mechanical properties of AG Carb which will be determined during testing. The AG Carb detailed test plan, however, has been revised to include all properties necessary to Stress to make a proper analysis of the design. Test results will not be available by PDR.

5. The expected radiation environment is listed in the Materials Problem Summary as being a maximum fluence of 1.4×10^{19} nvt. The fluence to which the AG Carb specimens will be subjected according to the test plan is 5×10^{18}. If the expected radiation environment is correct, the specimens should be irradiated at the same level.

D. NOZZLE SKIRT

1. The nozzle skirt will be subjected to low cycle fatigue for which the bending modulus of rupture is required. A typical panel section will have to be tested to account for stiffness of the structure.

E. PRESSURE VESSEL AND CLOSURE

1. The predicted environment should go as low as 40°R. Therefore, testing temperatures should be lowered to this value for the vessel materials.

2. Udimet 630 Bolts test radiation levels are at 10^{18}, while the expected exposure is 10^{19}.

5.101

F. VALVES

1. Various materials are under consideration for use in various valve designs and are not included in the composite Materials Test Plan was obtained. Of these, the Materials Department disallowed the use of 17-7 and 17-4 PH for springs. A better spring material will be specified for valve use. Phosphor bronze, beryllium copper, and beryllium nickel 440, for use as lip seals, are being investigated for suitability in cryogenic and radiation environments. These materials are not currently in the plan.

2. 301 SS sheet is the prime candidate for the valve and actuator seal. The problem summary lists radiation damage, Hydrogen embrittlement and physical properties as problems. However, the test plans do not include testing in these areas.

3. 718 and Udimet 630 bars are listed as prime and backup materials for the actuator springs. One problem anticipated is torsional modulus, however, no testing is scheduled for this property.

G. LINES

1. Some materials have been listed as having a radiation effect problem, but are not planned in the radiation testing. These are discussed in the Radiation Effect section.

2. The effects of welding are not adequately covered.

H. BOLTS

1. Fracture toughness is listed as a problem area, however, no tests are indicated to test for this property.

I. THRUST STRUCTURE

1. Al 2024-T6 sheet is listed as a prime material candidate for the upper and middle thrust structures and a backup material for the lower structure. The problems listed for this material are variability of mechanical properties, fracture toughness including compression, joint properties, fatigue resistance and radiation damage. However, the only test scheduled for this material is tensile without radiation, which may not be sufficient to solve

5.110

I. THRUST STRUCTURES (Cont'd)

2. The problem summary does not repeat the problems listed for the upper structure, even though the material candidates remain the same for the middle and lower structures.

3. Al 2024-T62, 6061-T6 and 7039-T63 are all listed as prime material candidates. It is not clear just which is the prime material to be considered.

4. Ti 6Al-4V is listed as the prime material for the lower thrust structure and compression as a problem area. No compressions tests are shown for this material.

5. Heat transfer properties such as K and $\mathcal{J}$, necessary to determine at what temperature, the part will be operating, are not listed for evaluation.

J. ELECTRICAL COMPONENT MATERIALS TESTING RECOMMENDATIONS

1. Since the actuators are to be electrical, consideration should be given to the insulating materials for use in solenoids and motors.

2. Samples of coated or insulated wire should be radiation tested to determine the effects of radiation upon the bonding of the insulation to the wire and changes in insulation resistance. Candidate coatings may be among the ceramics or polyemids.

3. Methods of terminating or joining wires should be tested, i.e., soldering, welding, swaging, etc.

4. Dry lubricants for bearings such as radiation M_oS and M_oS_e should be tested under radiation.

5. If magnetic powder clutches are to be used, the material properties of the powder under radiation conditions should be evaluated.

5.

TABLE I

COMPARISON OF MATERIALS TEST PLAN WITH IMPACT OF CO 70-1 [illegible]

MAJOR COMPONENT	MATERIALS PROBLEMS	DATA REQ'D	REFERENCE	COVERED BY TEST PLAN
TPA	Rolling element bearing life titanium and Inconel 718	Statistical life test	Memo 7740:M0379 7 Oct. 1969	Component Qual Tests planned.
	may be replaced by A286 for turbine	A286 data of same maturity as Ti & 718	"	No tests planned for Rad Effects. Otherwise similar maturity
Valves & Actuators	Hydrogen embrittlement of Inconel 718	Embrittlement at high H_2 pressure	Memo 7770:M6197 23 Oct. 1969	Yes, tests planned for sht., forging, tube, bar
	Wear of seals, bearings, gears	Part wear and life data	"	"C" data to be obtained for seals, bearings, gears
Pressure Vessel	Increased pressure cycling	Low cycle fatigue	"	Yes for 7039-T63 No, for 6061-T6
	Seal pressure cycling & wear	Part wear and life	"	None listed for PV seals, but some planned for 301SS
Thrust Structure	Stiffer structure may be required	Compressive "E" for 2024-T62 & Ti6AL-AV)Sht.	"	No tests listed for 2024-T62 sht. No comp. tests liste for Ti 6A6-4V sheet
Thrust Vector System	Wear of bearings	Part wear & life	"	"C" data to be obtained
Lines	(none identified by ref.)	-	Memo 7750:M0684 7 Oct. 1969	Yes
Nozzle Assembly	Coolant channel low cycle thermal fatigue	Thermal fatigue of 347SS or Hastelloy-X)Sht.	"	Yes, "C" data to be obtained by both

5.112

[illegible]

[illegible]

CRITICAL FAILURE MODE - ROTOR RUPTURE, BLADE FATIGUE

CRITICAL PROPERTY	PRIORITY	TEST	MAT'L (PRIME BACKUP)	SCHEDULE CY'70	SCHEDULE CY'71	SCHEDULE CY'72	REMARKS
TENSILE	III	70°F	Ti 5AL-2.5SN ELI-F	C — 1	— B	— A	[illegible]
	III	-423	Ti "	C — 1	— B	— A	
	I	70	Inconel 718	C — 1 — P	— A		[illegible]
	I	-423	" "	C — 1 — P	— A		
Thermal Expansion	II	-423	Ti	D — 1 — B			Why not "[illegible]" data [illegible] at some later date
	III	70 to -423	Inconel 718	D — 1 — C			
Damping Capacity	II	70	Ti	D — 1 — C			[illegible] for [illegible] prime mat'l at -423
	III	-423	Ti	D —	1 — C		
	II	70	Inconel 718	D — 1 — C			
	II	-423	" "	D — 1 — C			
Fracture Toughness	III	70	Ti	D — 1 — C			[illegible] plan for "[illegible]" data
	II	0423	Ti	D — 1 — C	— B	— A	
	III	70	Inconel 718	C —	1 — B		
	I	70	Inconel 718	D — 1 —	C — B		
					B	A	
Fatigue	III	70	Ti	C — 1 —	— B	— A	Why [illegible] CY'70? Prediction of [illegible] & [illegible] dependent on accurate analysis of rotor and blades which require this data
	I	-423	Ti	D — 1 — C	— B	— A	
	I	70	Inconel 718	D — 1 — C	— B	— A	
	III	-423	" "	D — 1 — C	— C	— B	

M E M O R A N D U M

TO: J. Yetto

DATE: 11 December 1959
7350:M0365

FROM: E. J. West

SUBJECT: Reliability Review of NERVA Specifications

COPIES TO: J. H. Ramsthaler, W. M. Bryan

Enclosure (1) presents changes required in the Reliability Sections only of the specifications we have received up to 12-9-59. Many other inconsistencies were observed during a cursory review of these specs, and we will gladly forward these additional comments if you desire.

E. J. West
Reliability
Reliability & Safety Analysis Section
Nuclear Rocket Operations

114

[illegible]

1. [illegible] Destruct System

   3.1.2.1 Change to "The reliability of the Destruct Subsystem shall be 0.9[illegible] or greater"

2. [illegible]-90177 Engine Instrumentation

   3.1.2.1 Change to "The reliability of the mission - critical engine control and diagnostic instrumentation measurements shall be 0.999917 or greater when engine operation is required"

3. [illegible]-90135 Pump Discharge Line

   3.1.2.1 Add "or greater" after .9[illegible]973

4. [illegible]-90264 Engine Purge Unit

   3.1.2.1 Add "or greater"

5. [illegible]-90152 Thrust Structure Subsystem

   3.1.2.3 Change to "The reliability of Thrust Structure Subsystem shall be 0.[illegible] or greater"

6. [illegible]-90121 Turbine Block Valve and Actuator

   3.1.2.1 Add "or greater"

7. [illegible]-90149 Turbopump Assembly

   3.1.2.1 Change to "The reliability of the TPA shall be 0.999831 or greater"

8. [illegible]-90179 Wiring Harness

   3.1.2.1 Change to "the reliability of control instrumentation distribution circuits and actuation power distribution circuits shall be 0.999[illegible]6 or greater".

9. [illegible] Structural [illegible] Coolant Lines

3.1.2.1 Add "or greater" after 0.[illegible]

10. [illegible] Pressure Vessel & Closure Subsystem

3.1.2.1 change to "the reliability of the PVCS shall be 0.999[illegible]7 or greater".

11. [illegible] External Shield Subsystem

3.1.2.1 Change to "the reliability of the external shield subsystem shall be 0.[illegible] or greater".

12. [illegible] Coolant Supply Control Valve & Actuator

3.1.2.1 Add "or greater" after 0.9[illegible]

13. [illegible]214 Instrumentation & Control Subsystem

3.1.2.1 Add "or greater" after 0.999214
[illegible] with a [illegible] confidence level"

14. [illegible] Block Valve & Actuator

3.1.2.1 Add "or greater" after 0.[illegible]642

[illegible] 116

MEMORANDUM

TO: P. P. Ventura

DATE: 12 December 1969
7850:M0368

FROM: J. H. Ramsthaler

SUBJECT: Reliability and Safety Analysis Section's Review of Pressurization and Actuator Gas Requirements, Data Item S-054-017

COPIES TO: W. M. Bryan, D. Buden, A. D. Cornell, R. V. Evleth, R. S. Fairall, R. B. Glasscock, J. M. Klacking, C. F. Leyse, B. Mandell, I. L. Odgers, D. E. Price, E. A. Sheridan, W. O. Wetmore
NTO: W. H. Bushnell

REFERENCE: (a) Memo 7010:2042M, P. P. Ventura to Distribution, dtd 9 December 1969, Subject: Pressurization and Actuator Gas Requirements, Data Item S-054-017

The Reliability and Safety Analysis Section has reviewed the subject report and find it acceptable as written.

for J. H. Ramsthaler, Manager
Reliability & Safety Analysis Section
Nuclear Rocket Operations

CLASSIFICATION CATEGORY
UNCLASSIFIED
CLASSIFYING OFFICER DATE

5.117

MEMORANDUM

To: C. W. Funk

Date: 23 December 1969
7850:0380M

From: F. C. Valls

Subject: Review of Material Test Plans

Copies to: W. M. Bryan, D. Buden, A. D. Cornell, W. E. Durkee, R. B. Glasscock, V. E. Kahle, D. J. Lamvermeyer, B. Mandell, A. J. Mihanovich, J. H. Ramsthaler, E. A. Sheridan, W. E. Stephens, E. J. West, File

Enclosure: (1) Table 1 - Material Test Plans

Review of the thirteen Material Test Plans listed in Enclosure (1) indicates that the physical material properties required for the application of Reliability analytical techniques to the design process have been substantially identified. However, the following recommendations are forwarded for your consideration:

1. Technical Comments

a. It is suggested that properties of composite sections, such as the reinforced graphite waffle extension and skirt tube bundle, be obtained from actual size test panels with appropriate radii of curvature. The values of the bending moduli of rupture B_{yk} and B_{uk} for these structures should also be statistically evaluated, since they are included as Stress Intensity Limits in SNPO-C-1.

b. Test Plans for the determination of material fatigue strengths and endurance limits should be changed to include values from notched ($K_T = 2,4$) as well as from mirror polished specimens.

c. Testing to define the "knee" of the fatigue curves will produce data of questionable accuracy. The "knee" is an arbitrary transition minimum strength curve through an area of maximum scatter band of points. Also, the location of the "knee" is greatly influenced by size, geometry, surface condition, residual stresses, frequency of stress application, etc., that preclude obtaining additive data that can be readily extrapolated. If operation is going to be near such areas, full scale testing or use of the endurance limit for the design is suggested.

d. Fracture toughness criteria as measured by the stress intensity factor K_{IC} should be referenced to the Fracture Mechanics Concepts of SNPO-C-1.

e. Creep data is more useful when related to percent rate of creep, rather than a rate.

5.115

2. Presentation Comments

a. It is preferable to have a specific statement of the material properties which are to be determined from a statistical frequency distribution of test specimens.

b. Whenever possible, utilize SNPO-C-1 approved nomenclature. Also, avoid inconsistencies in its use, such as using k_c (stress concentration factor) interchangeably with K_{IC} (fracture toughness critical stress intensity factor), "short transverse" meaning "radial" direction, and specify "Dynamic Moduli" as either tensile, bending, or torsional.

c. Qualify use of phrases such as "non-operational phase" when it should specify storage, handling or vacuum, "corrosion" for stress, fretting, galvanic corrosion, etc., and "general requirements" should be accompanied by a reference note.

A preliminary handwritten list with most of the above comments and with the respective page numbers, as well as the unsigned Test Plans with suggested corrections inserted, have been forwarded to the Materials Engineer for his consideration.

It is requested that a formal response to these suggestions be provided in order to provide a clear basis for our future reviews.

F. C. Valls

F. C. Valls
Reliability
Reliability and Safety Analysis Section
Nuclear Rocket Operations

Approved by:

W. M. Brown

for J. H. Ramsthaler, Manager
Reliability and Safety Analysis Section
NRO Systems Department

CLASSIFICATION CATEGORY
UNCLASSIFIED
W. M. Brown 12/31/69
CLASSIFYING OFFICER DATE

5, 11

Enclosure (1)

TABLE I

MATERIAL TEST PLANS

Material	Condition	Form
Al 6061	T6	Forging Weldments
Ti-6AL-4V	Annealed	Sheet Weldments
Vespel SP-1	Polyimide	Sheet
301 CRES	Annealed	Plate Weldment
A-286	Solution Treated, Aged	Forging Bar
Al 2024	T6	Forging Sheet
Bearing and Lubrication	Friction & Wear	Solid
Waspalloy	Cold Worked Aged	Bar Forging
Hastelloy	Annealed	Sheet
718 Inconel	Aged	Forging Bar
Graphite	Fibrous Graphite Composite	Allotropic
Ti-5AL-2.5 Sn (ELI)	Annealed	Forging
Udimet 630 Alloy	Cold Worked Aged	Bar
Al 7039	T63	Ring Forged Weldments
18 Ni	Maraging (Solution Treat, Aged)	Forge Bar Weldment